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SEA 32 MULTI-DOMAIN, MANNED-UNMANNED LITTORAL DENIAL SYSTEM

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SYSTEMS ENGINEERING ANALYSIS CAPSTONE REPORT

SEA 32 MULTI-DOMAIN, MANNED-UNMANNED LITTORAL DENIAL SYSTEM

by

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June 2023

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This report details a systems engineering approach to design a manned-unmanned, multi-domain, littoral denial system of systems, projected over the next decade. Mission context scenarios were created to provide diverse system operating environments, enabling a flexible system architecture to address a variety of threats in near-peer competition. With efforts to employ cost-effective and attritable unmanned components, open-source platform reviews were conducted to determine performance parameters, cost, and technical readiness levels, ultimately influencing the eligibility and appropriateness of these platforms for system integration. This evaluation led to a value system design for each candidate platform, providing quantitative analysis for its potential contribution to our system functions as they pertain to each mission scenario. An optimization program under cost constraints was then utilized to yield ideal platform combinations while meeting all functional requirements. Each architecture that resulted from the optimization program was then subjected to a combat model to verify its effectiveness, and then compared to conventional littoral denial constructs. Analysis and comparison of each system architecture yielded relevant insights for the project sponsor at OPNAV N9I (Director of Warfare Integration). Each scenario-dependent system of systems yielded improvements in certain functional evaluations, while also producing degradations in other functional areas.

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ABSTRACT

This report details a systems engineering approach to design a manned-unmanned, multi-domain, littoral denial system of systems, projected over the next decade. Mission context scenarios were created to provide diverse system operating environments, enabling a flexible system architecture to address a variety of threats in near-peer competition. With efforts to employ cost-effective and attritable unmanned components, open-source platform reviews were conducted to determine performance parameters, cost, and technical readiness levels, ultimately influencing the eligibility and appropriateness of these platforms for system integration. This evaluation led to a value system design for each candidate platform, providing quantitative analysis for its potential contribution to our system functions as they pertain to each mission scenario. An optimization program under cost constraints was then utilized to yield ideal platform combinations while meeting all functional requirements. Each architecture that resulted from the optimization program was then subjected to a combat model to verify its effectiveness, and then compared to conventional littoral denial constructs. Analysis and comparison of each system architecture yielded relevant insights for the project sponsor at OPNAV N9I (Director of Warfare Integration). Each scenario-dependent system of systems yielded improvements in certain functional evaluations, while also producing degradations in other functional areas.

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LIST OF ACRONYMS AND ABBREVIATIONS

AARP	Autonomous Attack and Reconnaissance Platform
AI	Artificial Intelligence
ASW	Anti-Submarine Warfare
BIRU	BLUE Initiatives for Regional Unity
BVR	Beyond Visual Range
C2	Command and Control
C5ISRT	Command, Control, Computing, Communications, Cyber, Intelligence, Surveillance, Reconnaissance and Targeting
CIFID	Climate Initiatives for Integrated Deterrence
CMC	Commandant of the Marine Corps
CNO	Chief of Naval Operations
CNR	Contrast-to-Noise Ratio
CONOPS	Concept of Operations
COTS	Commercial-off-the-Shelf
CRUSER	Consortium for Robotics and Unmanned Systems Education and Research
CS	Computer Science
DANets	Disposable Ad-hoc Networks
DDG	Guided-Missile Destroyer
DMO	Distributed Maritime Operations
DOD	Department of Defense
DPRK	Democratic People’s Republic of Korea
EABO	Expeditionary Advanced Base of Operations
EHF	Extremely High Frequency
ESE	Electronic Systems Engineering
EW	Electronic Warfare
GMBA	Gain and Maintain Battlespace Awareness

HF	High Frequency
IAMD	Integrated Air Missile Defense
IOC	Initial Operational Capability
IS&T	Information Systems & Technology
ISR	Intelligence, Surveillance, and Reconnaissance
JADC2	Joint All Domain Command and Control
LAD	Littoral Attachment Device
LDS	Littoral Denial System
LOS	Line of Sight
M&S	Modeling and Simulation
ME	Mechanical Engineering
MEU	Marine Expeditionary Unit
ML	Machine Learning
MLR	Marine Littoral Regiment
MMS	Multi-Mission System
MOE	Measures of Effectiveness
MOP	Measures of Performance
NDS	National Defense Strategy
NIWC	Naval Information Warfare Command
NPC	Near-Peer Competitor
NPS	Naval Postgraduate School
NSS	National Security Strategy
NWSI	Naval Warfare Studies Institute
O&M	Operations and Maintenance
OA	Operations Analysis
OTH	Over-the-Horizon
PRC	People’s Republic of China
RMP	Reference Mission Profile
SATCOM	Satellite Communications

SCUBA	Support for Cloud-Based Architecture
SE	Systems Engineering
SEA	Systems Engineering Analysis
SLOC	Sea Lines of Communication
SoS	System of Systems
SUW	Surface Warfare
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
UHF	Ultra High Frequency
UNREP	Underway Replenishment
USMC	United States Marine Corps
USV	Unmanned Surface Vehicle
UUV	Unmanned Undersea Vehicle
VHF	Very High Frequency
VLS	Vertical Launch System
WEZ	Weapon Engagement Zone
WIC	Warfare Innovation Continuum

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EXECUTIVE SUMMARY

A. INTRODUCTION

The Chief of Naval Operations Warfare Integration Division (OPNAV N9I) tasked the Systems Engineering Analysis cohort 32 to design a multi-domain, manned-unmanned, littoral denial system of systems, projected through the next decade (Pollman 2022). The project will include a concept of operations, detailed architecture, analysis, and subsequent recommendations for the *non-platform centric* littoral denial system. The cohort used the system engineering process as a guideline for project structure and incorporated skills learned from their systems engineering and operations research coursework.

B. PROBLEM STATEMENT

How might a non-platform centric, multi-domain, manned-unmanned system of systems contribute effectively to littoral denial efforts across the spectrum of conflict?

C. CAPABILITIES NEED

The system should be capable of countering all littoral domain threats, be hardened to electronic attack, provide kinetic and non-kinetic effects, conduct its own ISR and BDA, and be capable of adapting to multiple mission sets (Pollman 2022).

D. MISSION CONTEXT

The Department of Defense (DOD) is exploring how to best integrate unmanned systems with the current thinly spread force structure, allowing unmanned systems to bridge the gap while leveraging new capabilities and tactics. The littoral domain is an ideal operational space for these unmanned systems as it is traditionally not suited well for larger conventional combatants. Along with current focus on Great Power Competition with Russia and China, two scenario vignettes were created to provide mission context and serve as a basis for subsequent modeling and simulation. One scenario is the assistance to Swedish forces to prevent a Russian invasion of Gotland Island in the Baltic Sea. Another scenario created was defense of a Marine Corps Littoral Regiment serving as stand-in forces on the island of Palawan in the South China Sea, which also incorporates USMC Expeditionary Advanced Base of Operations (EABO) concepts.

E. MEASURES OF EFFECTIVENESS

A functional analysis was performed to define the mission and objectives, determine the system functions as well as derive the measures of effectiveness to evaluate the baseline and modified systems. The mission of the littoral denial system is defined as conducting littoral denial operations, with the overall objectives identified as maintaining operational and tactical initiative, preventing adversary access to sea routes and littorals, enabling friendly forces to operate effectively, and delivering uninterrupted firepower for battlespace denial and control. Through the functional decomposition process, four top-level functions were identified: Gain and Maintain Battlespace Awareness, Establish Battlespace Denial, Establish Battlespace Control, and Sustain Firepower. The associated measures of effectiveness to evaluate the performance of these functions are enemy detection (%), enemy attrition (%), friendly attrition (%), and simulations where friendly forces have their ammunition depleted (%), respectively.

F. DESIGN PROCESS

Following evaluation and scoping of the problem statement, along with determination of high-level functions and evaluation metrics, the team references the systems engineering process as a guideline to navigate the design process. Multiple relevant literature reviews were conducted along with lengthy unmanned platform research to influence system design and capability realization. Following the reviews and research, relative value rankings were assigned to platforms that were considered in the design. These values and their relative contribution to the system functions were run through a developed optimization tool to yield desired platform combinations that would become the littoral denial system of systems. These values could be modified based on importance and contribution to each scenario, which varied due to adversary capability, environment, and external support.

1. Platform Research and Literature Reviews

The cohort conducted reviews of high-level military strategy and key concept publications to help scope the breadth of the project, while incorporating strategic priorities to the system architecture. Also researched was a vast set of unmanned platform reviews, to include air, surface, and undersea domain platforms. These reviews provided insights to current and near-future unmanned capabilities for potential integration in the littoral denial system of systems design.

2. Value System Design

Following the unmanned platform reviews, key parameter data was collected regarding platform speed, depth (or altitude), endurance, weapon types, sensor types, and cost. From this data, the team was able to make relative comparisons between available and technologically ready platforms. Relative importance was also factored into this value design in the form of weighting factors. Similarly, each platform's potential to contribute to each of the four major functions was also evaluated. These evaluations were combined into a final value rating for each platform, which would serve as inputs to the system optimization tool.

3. Optimization

With the value ratings created for the different unmanned components comprising the Littoral Denial System, our team determined that a tool was needed to recommend an optimal combination of units needed to meet overall system requirements given the various constraints associated with developing and operating these systems. To accomplish this task, a mathematical optimization program was developed by the project team to maximize the value of the Littoral Denial System given overall programmatic constraints and value weighting, dependent on the different mission scenarios that the systems would be designed to address.

4. Mission Scenario Modifications

In order to ensure our littoral denial system is suited to missions in varying geographic locations, two scenarios were created, one on the island of Gotland and the other defending stand-in USMC forces on Palawan. Both scenarios were created for academic purposes and are designed to demonstrate system effectiveness against different adversaries and in different geographic extremes.

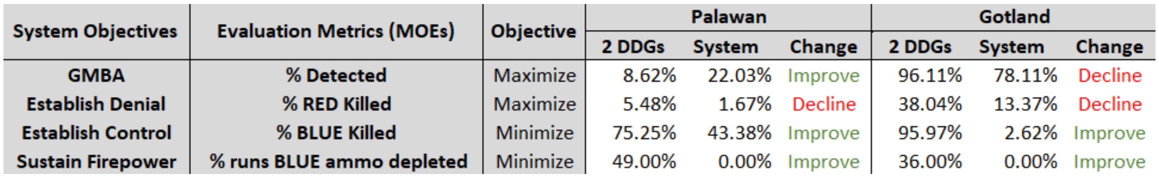
The Gotland scenario supposes a Russian assault on Gotland in response to perceived NATO pressure. Our system would be deployed alongside Swedish forces and traditional U.S. forces in area to deny Russian forces access to the littorals surrounding Gotland.

The Palawan scenario supposes a PRC invasion of Palawan with assets from its Southern and Eastern fleet. Our system would be deployed alongside traditional naval forces as well as a Marine EABO unit to deny PRC incursion into the Palawan littorals, allowing U.S. forces to defend Palawan.

G. COMBAT SIMULATION RESULTS

Simulations were run 100 times for each mission scenario using a traditional littoral denial force of two guided missile destroyers (2 DDGs), and 100 times with our scenario-tailored littoral denial system (System), which consisted of a variety of unmanned platforms in all domains. In each of these scenarios, the 2 DDGs and the scenario-specific system were also supported by traditional allied forces, dictated by the team-generated vignettes. Table 1 shows the average results of these simulation runs, in addition to how well each system was able to meet designed system functions.

Table 1. An overall simulation summary.



System Objectives	Evaluation Metrics (MOEs)	Objective	Palawan			Gotland		
			2 DDGs	System	Change	2 DDGs	System	Change
GMBA	**% Detected**	Maximize	8.62%	22.03%	Improve	96.11%	78.11%	Decline
Establish Denial	**% RED Killed**	Maximize	5.48%	1.67%	Decline	38.04%	13.37%	Decline
Establish Control	**% BLUE Killed**	Minimize	75.25%	43.38%	Improve	95.97%	2.62%	Improve
Sustain Firepower	**% runs BLUE ammo depleted**	Minimize	49.00%	0.00%	Improve	36.00%	0.00%	Improve

As shown, the designed systems performed well in certain areas such as Establish Control and Sustain Firepower, suggesting that friendly attrition is reduced and were more able to confront the enemy without running out of ammunition. However, the designed systems show a decline in the Denial function performance. The team's interpretation of the results, coupled with detailed knowledge of the optimization tool and value system design, suggest that substituting traditional platforms for unmanned platforms is the root cause due to replacing traditional kinetic weapons capability with unmanned platforms with limited weapons capability. Another possible cause for this performance is not factoring land-based missiles into the model, which would undoubtedly improve denial functionality. The final source of poor performance lies in the order of battle overmatch presented in the mission context scenarios, particularly for Palawan. With a higher ratio of capable enemy assets over available friendly assets (in all domains), the team's expectation for the system design was retrospectively ambitious, resulting in poor denial performance as evidenced by high levels of blue force attrition for the 2 DDG models.

GMBA, however, improved for the Palawan scenario, while degrading for Gotland. Early assessments suggest that the reason for this is due to the unique combination of unmanned platforms selected by the optimization tool for each scenario. Specifically, a large quantity of mines was selected for the Gotland problem to counter the Russian submarine threats, which does not have a high sensor performance value.

H. CONCLUSIONS AND RECOMMENDATIONS

Through the systems engineering process, we have developed an iterative approach to force design that, through further research, can serve the Navy through the next decade at a minimum. Given the project's high level of scope, we tried to be as accurate as possible when it came to the modeling and simulation of our system. However, the unclassified nature of the project, limited performance metric availability, and the modeling language used challenged our team to maximize the project's full potential. Due to simulating an overmatched scenario, withholding contributions from land-based missiles, and a mismatch in sensors and weapons across domain threats, the optimized system failed to increase our ability to deny littoral space to hostile forces. Despite these challenges, we were able to show that altering the functional and domain weighting can produce unique optimized systems for specific mission sets and geographic locations.

Another realization is that weapon capacity limitations continue to be a factor in the lethality of our designs. As shown, we were able to increase our battlespace awareness, control, and sustainment metrics, however, the denial metric, attributed as lethality, was diminished in both scenarios from our initial two DDG force. We suspect that the lack of weapons capacity on each unmanned platform, along with the prohibitive cost of modern weaponry, influenced the optimization tool to purchase less-lethal platforms to meet the cost requirements. If the cost of weapons can be reduced, we believe that a distributed and lethal force is possible.

References

Pollman, Anthony G. 2022. “FY2022 SEA32 Capstone Project: Tasking and Timelines.” Memorandum. Monterey, CA: Naval Postgraduate School, Systems Engineering Department.

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The team also thanks the professors in the systems engineering and operations research departments for their professionalism and expertise as the team navigated the systems engineering analysis program. The knowledge and skills acquired throughout their course work provided the team with the proper tools to embrace the challenges of littoral denial system design.

The team would also like to thank their project sponsor and support staff at OPNAV N9I who provided the team with the opportunity to study at the Naval Postgraduate School and provided guidance to frame the project problem.

Special thanks to project advisors Dr. Fotis Papoulias, Dr. Jefferson Huang, Dr. Roberto Szechtman, and CAPT Jeff Kline (USN, Ret.) for their unique perspectives, professional knowledge, and continual guidance throughout the design process.

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I. INTRODUCTION

This section provides an overview of the initial framework for our project design. Along with explicit project tasking, the reviews below show previous works, related civilian symposiums on force design, and provide brief introductions to the project team and relevant stakeholders.

A. PROJECT BACKGROUND

This chapter presents several fundamental components that influenced the implementation of the project. Through an examination of these elements, readers will gain insight into the underlying rationale for certain assumptions that were made. The key components that comprise the project's foundation include the Warfare Innovation Continuum (WIC), the most recent System Engineering Analysis (SEA) project, the Tasking Statement, and the Project Stakeholders.

1. Warfare Innovation Continuum

The Warfare Innovation Continuum workshop, sponsored by the Naval Warfare Studies Institute (NWSI) and the Consortium for Robotics and Unmanned Systems Education and Research (CRUSER), was held from September 19–22, 2022 at the Naval Postgraduate School's (NPS) Monterey campus and 'Virtual Campus via ZoomGov. This event provided an opportunity for NPS students to interact with faculty members from various departments, fleet officers, and guest engineers from Naval laboratories, warfare centers, and system commands, as well as industry experts and professionals. Of note, representatives from Johns Hopkins University Applied Physics Lab, Naval Information Warfare Command (NIWC), Raytheon, and Lockheed Martin participated, and international representation from countries like the United Kingdom, Mexico, Brazil, Netherlands, Japan, and Australia provided unique global perspectives. The workshop was designed to encourage a focused collaboration among the participants and facilitators.

The 2022 edition of the WIC Workshop, titled "Future Hybrid Force," encouraged participants to employ new technologies to influence force structure and change the way we would fight a global conflict in 2045, envisioned through a NWSI fictional scenario (Englehorn 2022). There were 138 participants registered in a variety of roles, including concept generation team members, facilitators, panelists, mentors, and observers. The attendees represented over 50 organizations, and although the majority of concept generation participants were in-resident students from various NPS programs, some faculty and industry professionals also contributed in this capacity.

The workshop organizers proposed the creation of seven different concept generation teams (Cloud, Deter, Fires, Littorals, Logistics, C5ISRT, and USW), each with their own unique tasking. Team Cloud was tasked with exploring cloud computing at the tactical edge, which involved identifying relevant naval stakeholders and addressing the challenges associated with gaining sufficient computation power for mission success, in all domains. Team Deter was responsible for "exploring the framework for working across warfighting domains, theaters, and the spectrum of conflict, in collaboration with all instruments of national power, as well as with U.S. allies and partners" (Englehorn 2022). Team Littorals was tasked with approaching the overarching design challenge through a coordinated littoral warfare lens, exploring the coordination of a wide variety of unmanned and manned forces conducting operations in coastal areas.

Meanwhile, Team Fires was tasked with exploration of kinetic and non-kinetic weapons systems of varying lethality, which were then integrated into existing systems to provide assisted targeting, coordinated joint fires, as well as Integrated Air and Missile Defense (IAMD) (Englehorn 2022). Team Logistics was tasked with exploring how to maintain operations in a sustained engagement along the spectrum from competition to conflict, in coordination with allies and partner nations. On a classified-secret level, Team C5ISRT was responsible for exploring information and communications collection, how it moves is received, transferred, and operationalized, in addition to counter-C5ISRT efforts. Team USW, also at a secret level, was tasked with exploring issues and solutions for undersea domain assets and infrastructure.

On the final day of the workshop, each team presented their final briefs, with each team given 15 minutes to present their most promising concepts. Below is a brief, non-classified overview of the concepts proposed by each concept team. Though not presented here, full summaries of the classified presentations are available through NWSI appropriate channels.

1. C5ISRT/Kill Web. This concept uses advanced sensors from Joint All Domain Command and Control (JADC2) and Artificial Intelligence (AI) / Machine Learning (ML) to enhance decision-making at the tactical level, allowing for more effective missions and results.
2. CLOUD/SCUBA. This concept involves a local cloud mesh network known as Support for Cloud-Based Architecture (SCUBA). It uses a cloud database located on one or more ships within range of other ships to provide a strong, reliable connection for sharing a powerful database without relying on vulnerable satellite communications or land-based databases.
3. DETER/CIFID. This concept includes Climate Initiatives For Integrated Deterrence (CIFID), such as BLUE Initiatives for Regional Unity (BIRU) and the "BLUE Economy" Development Fund.
4. FIRES/AARP. This concept involves the use of a configurable force of modular unmanned aerial vehicles (UAVs) called the Autonomous Attack and Reconnaissance Platform (AARP) to deploy disruptive fire effects, addressing the current gap in our forces' ability to reach People's Republic of China (PRC) forces deep within their deny area.
5. LITTORAL/PROJECT. This concept includes two sub-concepts: the Mobile Observation and Sensing Quick Unmanned Intelligence, Surveillance, and Reconnaissance (ISR) and Targeting Object (MOSQUITO), which provides pre-staged swarming autonomous systems to naval expeditionary forces, and the Littoral Attachment Device (LAD), which supports the sea denial mission in the littorals. Both concepts use Disposable Ad-hoc Networks (DANets) for coalition operations.
6. LOGISTICS/The Continuum. This concept involves estimating bulk energy needs, identifying storage locations, engaging key stakeholders,

finalizing planning and design, executing pilot programs, and exercising operations, leveraging underwater bladders and concealed shore-based facilities.

7. USW/MMS. This concept involves the Multi-Mission System (MMS), which enhances existing unmanned undersea vehicle (UUV) platforms and technologies to provide improved battlespace awareness and agility to operational commanders in all phases of conflict.

At the WIC's conclusion, mentors considered two generated concepts as the most relevant. The first is called SCUBA (Support for Cloud-Based Architecture), which is a local cloud network that uses a cloud database located on one or more ships within the transfer range of other ships. This network will provide a strong and consistent connection, allowing the fleet to share one powerful database that is updated with new information without relying on vulnerable satellite communications or land databases. The second notable concept, AARP, configures a modular force of UAVs to deploy disruptive fire effects. Currently, it is assessed that our forces cannot reach PRC forces deep within their deny area, but the AARP concept aims to address this gap (Englehorn 2022).

Our team was able to participate in four of the seven teams' concept generation efforts, exposing our team to a variety of scenarios, problems, and proposed solutions in this dynamic exercise. Not only did the presented problem scenarios give our team a related issue to consider, but we were also able to begin formulating innovative ideas with the help of colleagues, mentors, and industry leaders, providing a foundation for subsequent Littoral Denial System (LDS) design.

2. Past SEA Project – SEA 31

System Engineering Analysis cohort 32's project tasking continues to build on previous cohort's capstone projects and is particularly related to SEA 31's project. Their project's mission was to design a System-of-Systems (SoS) to "counter anti-access and area denial capabilities of near peer adversaries, cost effectively by the year 2025" (Brown et al. 2022b). In their work, the South China Sea and the PRC forces were taken as a reference warfare environment and adversary, along with several reference warfare scenarios. Moreover, the system is assumed to be carried aboard, deployed, and operated from a DDG. Though SEA 32's tasking continues their work, the project will shift focus toward a non-platform centered solution.

Their working process started by identifying the main tasks they believe their designed system should contribute collection operations and management, target attacking, and communication, in addition to several over-the-horizon (OTH) functions. Then, three different measures of effectiveness (MOE) were defined for the system: number of hits on enemy platform, hits on own platform, and cost of the system. Their process continued by comparing the cost-effectiveness of unmanned platform in three categories: delivery, communications relay, and attack capabilities, where their performance was evaluated using a multi-attribute value analysis. Based on these comparisons and the system function requirements, a variety of models and simulations were used as analysis tools (PYOMO – optimizer software, combat simulations such as salvo combat model, and agent-based modeling and simulation) to determine an optimal platforms combination.

The result of the SEA 31 project is a proposed architecture for the SoS, while providing interesting insights and recommendations following the research process. Although SEA 32's project strives to provide a non-platform specific solution, similar ideas, analyses, and lessons learned from SEA 31's capstone project are easily transferrable to SEA 32's tasking. One particular insight from SEA 31 is that cost-effectiveness can be achieved through enhancing current capabilities rather than devising new ones.

3. Tasking Statement

With the SEA 31 project results and WIC serving as a foundation to the project, the team was able to begin scoping efforts, utilizing the SEA 32 project tasking memorandum as a guide. This tasking states:

> *Building on the SEA 31 project, and reaping lessons learned from all the NWSI research task forces and campaign of analyses activities, SEA 32 will focus on "Engineering and Analysis of a Multi-domain, Manned-Unmanned Littoral Denial System." Using principles from your coursework, augmented with your warfighting experiences, develop a proposal for an operational concept, operational analysis, architecture, and detailed design of a non-platform centric, system of systems, multi-*

> *domain, manned-unmanned littoral denial system for a specified scenario and mission of your choice.*
>
> *Your system will need to address countering all levels of threats: air, surface, and sub-surface while being hardened to threats from cyber and electronic warfare. It may also provide decoy services and could incorporate a network of mobile mines or other future capabilities and concepts. The multi-domain manned-unmanned littoral denial system should encompass its own ISR, non-kinetic and/or kinetic weapons, and BDA; however, these capabilities could and should be generated by a network of small, risk-worthy, manned-unmanned systems (i.e.: NOT platform centric; think more like an Aegis system).*
>
> *Missions might include Full Spectrum ASW; Littoral Warfare (Strike); War at Sea Strike (Long Range Fires); Port/Base Security; Integrated Air and Missile Defense; Maritime Interdiction Operations (Grey Zone activities); Protection of Underwater Infrastructures; or others. To the greatest extent possible, SEA 32 should seek to identify areas of utility and synergy across all mission areas, meaning: if a different mission were to be executed, your system should be able to adapt.*

The complete project Memorandum for SEA 32, which includes additional guidance and timeline expectations, can be found in Appendix A. However, from the team's analysis of the tasking statement, it was evident that the LDS presented several design challenges. The first broad challenge identified was to ensure that the system of unmanned systems would be able to conduct the identified mission sets across all domains and various environments. Similarly, the LDS should be capable of global utilization across the full spectrum of military operations. As a result of this initial analysis, our team expected that many different capabilities would need to be engineered into the system, some of which may conflict with each other. Another notable design challenge is that this system must be designed to compete with peer and near-peer adversaries. These adversaries, particularly China or Russia, have a large array of capabilities across various domains that they can utilize against naval forces. With this in mind, competition inside an adversarial weapons engagement zone requires that the system design should simultaneously address air, surface, and undersea threats.

Additional design challenges result from the relatively short timeline, projected to the next ten years (2033). Along with various unknown aspects injected into the scenarios, base assumptions and adversary posturing are likely to change in the 10-year timeline. Due to the rapid pace of technological progress, it is also likely that there will be significant technological developments within this timeline that may upset current mil-tech paradigms, such as quantum computing impacts on cryptographic communications or machine learning effects on weapons release authorities. Additionally, the fluidity of the current and future geo-political situations indicates that this system needs to be flexibly designed for a broad range of missions. Along with these unknown variables, this 10-year timeline is relatively short for the DOD procurement cycle, where innovative approaches must be considered in the design process to address all aspects of the complicated tasking.

4. Project Stakeholders

Along with the SEA 32 cohort, there are various entities (or stakeholders) that hold interest in our project's process, system design, and resulting insights. In addition to the cohort, our advisors in the Systems Engineering and Operations Research department have a shared interest for our team to not only meet graduation requirements, but to improve our knowledge and experience by navigating the SE process first-hand to yield relevant insights and recommendations to our project sponsor and decision-maker at N9I (Director of Warfare Integration). A list of immediately relevant stakeholders is shown in Table 1, though it should be noted that this list may extend to policy makers, contractors, and the warfighter should our project yield sufficient results to warrant a program of record.

Table 1. List of Stakeholders for SEA 32 Capstone Project. Adapted from SEA 31 (2022).

Stakeholder	Type	Interest
Director, Warfare Integration (OPNAV N9I)	Decision-Maker, Sponsor	• Insight, analysis, and recommendations for systems, architectures, and concepts of operations • Recommendations to close capability gaps and identify tradeoffs
Deputy Director, Integrated Warfare (OPNAV N9IB)	Decision-Maker, Sponsor	
OPNAV N9I Chair of Systems Engineering Analysis Jeff Kline, CAPT, USN (ret.)	Advisor	• Completion of graduation requirements • Relevant recommendations to OPNAV N9I
Systems Engineering Advisor Dr. Fotis Papoulias Operations Research Advisor Dr. Jefferson Huang	Advisor	• Assist SEA cohort with graduation requirements • Meet teaching syllabus of SEA project
SEA32 Student Cohort	Analyst	• Complete graduation requirements • Apply critical thinking and reinforcement of curricula skills

B. PROJECT TEAM

The SEA 32 capstone team consists of a diverse background of eighteen military and civilian personnel, to include representation from Singapore, Brazil, Israel, and the United States, accounting for industry professionals and military servicemembers from the Army, Navy, Air Force, and Marine Corps. Each member of our team has unique undergraduate and professional experience, in addition to varying fields of study here at NPS, allowing us to leverage a diverse range of engineering and military expertise.

Table 2 lists each team member along with their country of origin, occupation, and field of study at the NPS.

Table 2. SEA 32 Capstone Project Team List

Name	Rank/Service	Country	Curriculum
Anderson, Alex	LCDR, USN	U.S.	590/ESE
Chea, Wei Tien	ME5, Army	Singapore	360/OA
Figlioli, Jordan	Capt, USMC	U.S.	370/IS&T
Figlioli, Susan	Capt, USMC	U.S.	370/IS&T
Koh, Alvin	Civ, ST Engineering	Singapore	580/SE
Kwan, Justin	MAJ, Navy	Singapore	308/SEA
Loh, Charles	CPT, Army	Singapore	580/SE
Peh, Wesley	CPT, Army	Singapore	590/ESE
Seow, Aaron	CPT, Army	Singapore	580/SE
Seri, Matan	LT, Navy	Israel	360/OA
Simoes-Ferry, Daniel	MAJ, Air Force	Brazil	308/SEA
Song, Meng Wee	Civ, ST Engineering	Singapore	368/CS
Stanislav, Alexander	LT, USN	U.S.	308/SEA
Su, Juncun	ME5, Air Force	Singapore	570/ME
Thng, Lianquan	Civ, ST Engineering	Singapore	580/SE
Wasson, Zachary	LT, USN	U.S.	308/SEA
Witte, Matthew	LT, USN	U.S.	308/SEA
Yeo, Jun Yi	Civ, DSTA	Singapore	360/OA

The SEA 32 team was initially organized into teams based on their individual expertise, experience, and interest level. Throughout the project, however, this organizational structure was altered based on deadline requirements, team member availability, and project needs. Generally, however, the team was divided into domain sub-teams, led by military subject matter experts (SME) in each corresponding domain of Air, Surface, Undersea and Communications / Command and Control (C2). Throughout the systems engineering (SE) process, the C2 team was eventually dissolved and spread out to the remaining domains, providing a communications bridge between domains. Another team assignment shift occurred when it became time for modeling and simulation (M&S) efforts to commence. Under the guidance of our Operations Research advisor, the M&S

team consisted of those team members in the Operations Analysis (OA) degree track, as well as others who have M&S skills.

II. LITERATURE REVIEWS

The team conducted numerous reviews of key publications that were considered relevant to LDS design. These reviews provided the team with information to scope the problem and ensure that the design process was aligned to higher level strategic and operational guidance, while also exposing the team to specific capabilities of unmanned system platforms. Summaries of these literature reviews are provided below.

A. 2022 NATIONAL SECURITY STRATEGY

The United States National Security Strategy (NSS), one of the most important U.S. national security documents sets the overall national strategic ends, ways, and means for the nation. For U.S. military program development, the NSS is an important document as the highest-level strategy informs the requirements development for future military capabilities. For this LDS project, it was important to align our system to the NSS so that the system would be relevant to the current security environment and future challenges with near-peer competitors.

There are five Sections in the document that describe how the U.S. intends to execute its strategy. The first Section, titled "Competition for What Comes Next," covers the overall strategic situation for United States, including the challenges the nation faces and our approach to deal with these issues. Here, the role of America is described as leading a "free, open, secure, and prosperous world" to support American security (White House 2022, 7). One of the major challenges identified for the U.S. is the global struggle between democracies versus autocracies and the associated "powers that layer authoritarian governance with a revisionist foreign policy" (White House 2022, 8). Another test to America's role is the various shared global challenges that "do not respect borders and affect all nations" (White House 2022, 9). One of these 'shared global challenges' is the need to address climate change, which is noted as the "greatest and potentially existential [problems] for all nations" (White House 2022, 9). To reassert America's role and face these challenges, the NSS recommends an approach of investment in national power, connection through diplomacy, and strengthening of the military.

The next Section, titled "Investing in our Strengths," lines of effort to strengthen America's instruments of national power, specifically diplomacy and the military, are discussed. Then, in the "Our Global Priority" Section, specific challenges from great power conflict are covered, where shared global challenges and challenges to international rules are explained. In the next section, "Regional Strategy," application of this strategy in different regions around the world is explained. All main strategic ideas are then summarized in the final "Conclusion" Section.

For SEA 32's LDS, there are various aspects of the NSS that are applicable to system design and development. One of the overarching themes of the NSS is the importance of allies and partners to U.S. national security. Therefore, if this LDS is to be relevant in the current security environment, it will need to be interoperable with other nations. This desire for operation with allies and partners will likely influence the development of this LDS as requirements "interoperability and joint capability development" will need to be incorporated into the system design (White House, 22). Another applicable aspect for the LDS is the global role of the U.S. and the need for forward posturing of U.S. capabilities. Again, designing for current relevancy, the LDS must be able to be used in a variety of global locations. This desire for a system that can be used in global littoral missions will likely influence engineering design factors such as weather patterns, geographic location, littoral sea parameters to include vessel traffic patterns and density, and the threat environment.

Another aspect of the NSS that is important to the development of this system is the concept of Integrated Deterrence, where the utilization of all domains of state power, beyond just military, are used to provide "the seamless combination of capabilities to convince potential adversaries that the cost of their hostel activities outweighs their benefit" (White House 2022, 2). The LDS will enhance its effectiveness if Integrated Deterrence is considered early in the system design phase. Another aspect of the NSS strategy that may influence system design is the importance of a cross-domain strategy. If this littoral system is to be successful, it must be able to be a tool that can be utilized across multiple domains (surface, air, undersea, space, etc).

The importance of the great power challenges that Russia and China present is yet another aspect of the NSS that must be considered for this system. If this system is to be successful, it must be designed to deliver capabilities against the threats from these nations. The LDS should also aim to utilize, and perhaps counter, new technologies in its design, as the NSS identifies emerging technologies to be key contributions for adversary's pacing efforts. Finally, due to the NSS's focus on competing across a range of military operations, it will be important to engineer this system so that it can conduct a range of different operations to remain a relevant system, regardless of employment location and mission set.

B. 2022 NATIONAL DEFENSE STRATEGY

Informed by the NSS, the National Defense Strategy (NDS) is the top-level document from the Office of the Secretary of Defense that sets the overall defense strategy for the DOD. This is an important document for any defense program as it sets the department specific strategy that informs the requirements development process. For this LDS, it was determined that a review of the NDS during this literature review stage was essential as it informed the basic requirements to help ensure that the system developed is relevant to the current security environment and aligned with the DOD's overall strategy.

The first part of this document details the overall security environment that the DOD must operate in. The primary military threats from both China and Russia are discussed along with several "Other Persistent Threats," such as Iran's quest for a nuclear weapon, North Korea's missile programs, and violent extremist organizations. Beyond the conventional military threats, other operations, to include "Grey Zone Actions" by state actors, are aspects to be considered in the current security environment.

The following Section of the NDS notes the overall department priorities. In no particular order, these include defending the homeland from the PRC's multi-domain threat, deterring strategic attacks against U.S. and allies, deterring aggression, and building a resilient joint force and defense ecosystem (Office of the Secretary of Defense [OSD] 2022, 7). To achieve these priorities, the NDS states that it will utilize the concepts of "Integrated Deterrence" and "Campaigning," where Integrated Deterrence is defined as the process of "working seamlessly across warfighting domains, theaters, the spectrum of conflict, all instruments of U.S. national power and our network of Alliance and partnerships" (OSD 2022, 1). Both methods of deterrence are discussed (e.g., deterrence by denial, determined by resilience) as well as theater specific application of deterrence concepts.

The next Section of the NDS discusses the concept of "campaigning," defined as "the conduct and sequencing of logically linked miliary activities to achieve strategy aligned objective over time" (OSD 2022, 12). The application of campaigning throughout the spectrum of military operations is also mentioned to include the context of "grey zone" operations that span the models of peace and war operations. Inherent to campaigning operations are aspects that incorporate close partners and allies into the overall defense strategy. Here, each geographic theater is analyzed to identify how different U.S. allies can be leveraged to further U.S. and global security priorities. Following the discussion on relationships with allies and partners, the NDS notes how the department should approach force planning and development, noting how the department can utilize "enduring advantages" to support the department's overall mission. Finally, the documentation discusses risk management issues related to the entire DOD enterprise.

There are several aspects of the NDS that are relevant to the development of the LDS. For example, the NDS's focus for the DOD to prepare for a range of military operations, including "grey zone activities," means that for this system to be relevant to the current defense environment, it will need to be designed to function across a spectrum of operations. Additionally, the priority to address multi-domain threats from peer competitors such as the PRC means that this system should be designed to operate effectively across multiple military domains. The global reach of the DOD's mission as described in the NDS also means that for this system to be relevant, it must be designed for global operation in diverse environments. The NDS focus on strong partnerships also implies that the system design should consider integration with our allies' current and near-future systems.

The different aspects of deterrence discussed in this NDS will also influence the overall LDS design. The concepts of deterrence by denial will likely be especially relevant as the system is explicitly designed to deny the littoral area to potential enemy threats.

Deterrence by resilience and cost imposition are also notable concepts that will be considered for system design. Additionally, the approaches for deterrence against specific state including the PRC, Russian, Democratic People's Republic of Korea (DPRK), and Iran that are discussed in this document may inform how this system is designed.

The concept of "Escalation management" discussed in this document is another NDS aspect that may be utilized in the system design. To properly achieve deterrence capability, tools are needed to both properly calibrate military response to a situation and assess its impact, which are aspect considerations for system design integration. This concept of escalation management is connected to the project tasking for this LDS which notes that this "should encompass its own ISR … and BDA" (Pollman 2022, Tab A). These functions of sensing the environment, that were desired in the tasking statement, could be utilized by this LDS to enable this strategic function of escalation management.

For this develop system to be relevant to the DOD, it will also need to be aligned to the NDS's future force priorities of being: Lethal, Sustainable, Resilient, Survivable, Agile & Responsive (OSD 2022, 18). In the development and design of this system, these aspects should be guiding design principles that are continually referenced to ensure our system design remains focused. Finally, the NDS's desire to acquire and field systems more quickly is another aspect that should be incorporated into the development and design of this system, where methods of procurement (Commercial off-the-Shelf (COTS) products) and platform technology sharing will be considered for efficient product acquisition.

C. CHIEF OF NAVAL OPERATIONS NAVIGATION PLAN 2022

The Chief of Naval Operations (CNO) Navigation Plan identifies the CNO's priorities for maintaining maritime dominance. There are three distinct trends leading to increasing lethality and complexity of the battlespace: the erosion of credible military deterrence, increasingly aggressive Chinese and Russian behavior, and the accelerating pace of technological change. To maintain credible deterrence the Navigation Plan directs the Navy to focus on six overarching Force Design Imperatives: expand distance, leverage deception, harden defense, increase distribution, ensure delivery, and generate decision advantage. These imperatives will be facilitated by investing in integrated combat systems, networked enabled distributed forces, and new, lethal platforms. The CNO intends to build new platforms to support Marine Expeditionary Units (MEU) and provide maritime maneuver for Marine Littoral Regiments (MLR) to operate in contested environments in support of the United States Marine Corps' (USMC) EABO. The Navigation Plan states, that "to build the dynamic kill chains required for distributed maritime operations (DMO), we must modernize and integrate current capabilities for Long Range Fires, aligning our analysis, prototyping, experimentation, requirements documentation, and capability development." (Office of the Chief of Naval Operations 2022, 18)

D. DEPARTMENT OF THE NAVY UNMANNED CAMPAIGN FRAMEWORK 2021

The U.S. Navy's Unmanned Campaign Framework outlines the benefits that unmanned platforms currently have, while highlighting their proposed capabilities that will allow for future force structures. The framework also identifies current DOD unmanned systems across the air, land, surface, and undersea domains, and proposes a strategic framework that will allow this vision to become an integrated reality to the future force.

The push for unmanned, and even autonomous systems, to be integrated with the current force aligns with the Navy's DMO concept, providing a lethal, affordable, connected capability. Networked unmanned systems also increase force agility, operational tempo, and combat readiness, provide extended battlespace awareness, all while reducing or eliminating the risk to human operators. With the plan for unmanned platforms to augment existing combat platforms, increased mission risk can be addressed while maintaining the tactical and strategic advantage. Ultimately, these platforms can be effectively and reliably deployed where traditional platforms cannot, increasing deterrence capabilities and force survivability.

The DOD's Unmanned Portfolio consists of the platforms listed below, which are considered for our system. Unmanned land platforms are also identified in the framework but are out of the scope of our project.

- Air. 30+ years of UAS experience in USMC and USN, primarily focused on ISR&T missions with varying payloads (MQ-8C Fire Scout, MQ-4C Triton, MQ-9A, MQ-9A Stingray, UAV V-BAT, Stalker UAS, etc.)

- Surface. Sea Hunter 1 and 2, influencing Large and Medium Unmanned Surface Vehicle (USV) prototyping efforts, equipped with sensor capabilities, and serving as supplemental magazines to traditional force platforms.

- Undersea. XLUUVs (ORCA) for large payloads, Snakehead and Razorback S/MUUV for shallow, deep, and exceedingly dangerous operations. Mk-18 for MCM missions.

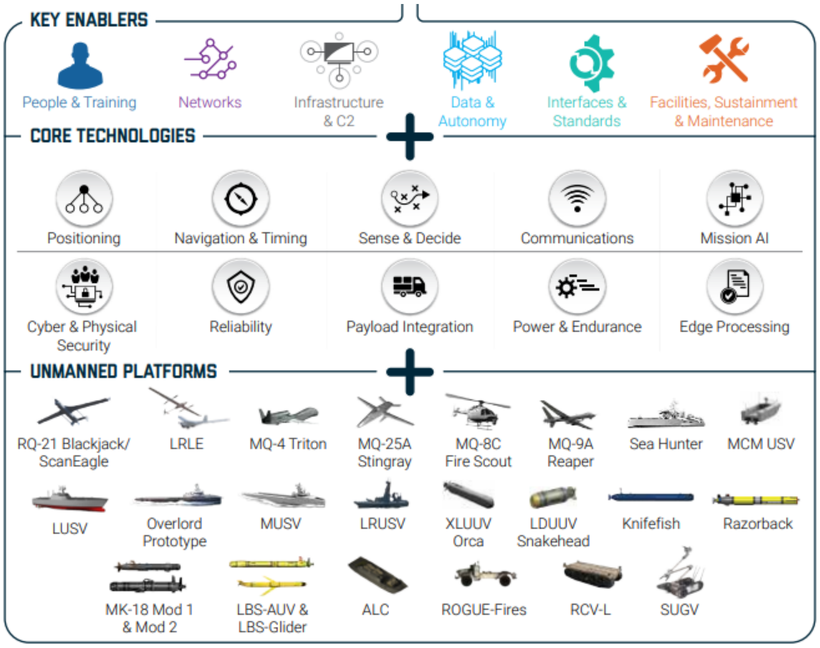

Figure 1. Identifies Support Enablers, Core Technologies, and Existing Unmanned Platforms. Source: Office of the Secretary of the Navy (2021).

Although a variety of unmanned systems exist and are employed throughout the DOD, a shift from the traditional platform-centric, novel technology focus to one that prioritizes capabilities will be required to successfully integrate these emerging technologies into existing force structure. This will not go unchallenged, however, as technical, political, and fiscal barriers continue to exist in all defense acquisition efforts. Programs will need to improve their research and resourcing efforts through studies, analyses, modeling and simulations, wargaming, and exercises. Another key aspect of the framework addresses the competitive fiscal environment within the DOD, stating that unmanned programs will need to find commonalities with other program of record systems, where technological investment will cut across multiple platforms.

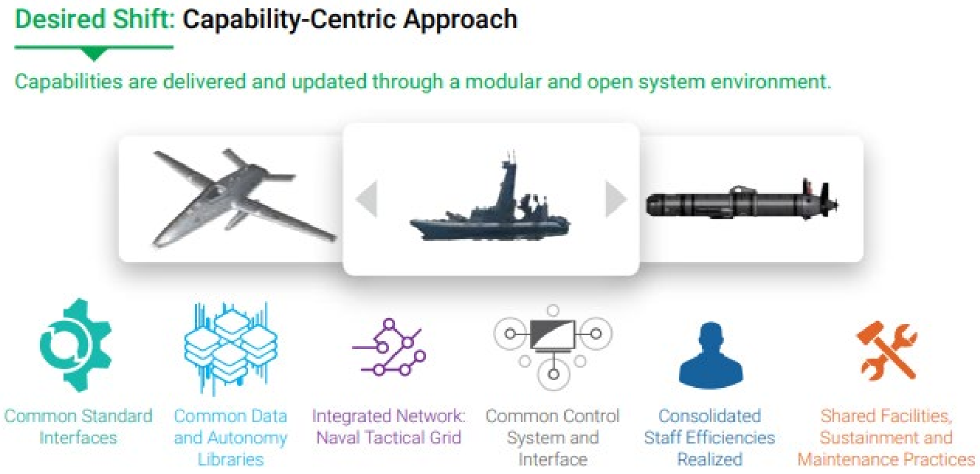

Figure 2. DOD’s Capability-Centered Approach. Source: Office Secretary of the Navy (2021).

E. TENTATIVE MANUAL FOR EXPEDITIONARY ADVANCED BASE OPERATIONS 2021

The primary reference for EABO is the Tentative Manual for Expeditionary Advanced Base Operations, organized by LtGen Eric Smith and published in February 2021. The manual was founded from over one hundred years of military doctrine, and the concept for EABO was officially signed in March 2019 by the CNO and Commandant of the Marine Corps (CMC) (United States Marine Corps [USMC] 2021), incorporating Navy and Marine Corps doctrine from the decade prior to September 11, 2001.

The approach to warfare practiced throughout the Global War on Terrorism in Iraq and Afghanistan will not be easily transferrable to the types of conflict anticipated in the manual. In contrast to a complete asymmetrical technical advantage, the manual acknowledges that near-peer competitors (NPCs) such as China “have developed, acquired, and fielded modern, state-of-the-art information technologies of their own to disrupt and exploit the U.S. military’s information dependence” (USMC 2021, sec. 1–3). As opposed to massing a force of tens of thousands of personnel at an individual location over several months, the manual prescribes forces to “disperse as widely as possible,” “carefully manage their signatures,” and rely on distributed prepositioned supply caches instead of large supply trains from a central repository (USMC 2021, sec. 3–2).

The manual further elaborates that “signature management is critical to the survivability of Marine forces executing EABO missions within the adversary’s Weapon Engagement Zone (WEZ). The ability to alter or limit observable and measurable signatures will preserve and extend the capabilities and proficiency of personnel and systems supporting EABO by making them more difficult to identify and target” (USMC 2021, sec. 4–10). Therefore, our system must be capable of managing their Electronic Warfare (EW) emissions or risk detection, and possibly destruction.

The manual summarizes the gaps in warfighting today with a description of the ideal Marine infantry battalion. LtGen Eric Smith, the author of the EABO concept, states: “Infantry battalions must be organically equipped, starting at the squad level, with resilient, networked communications and precision fires capabilities, including loitering munitions enabled by artificial intelligence. These units must be light, mobile, and capable of distributed operations… And they must be armed with organic systems capable of sensing, cueing, and shooting in support of naval and joint sea control and assured-access missions” (USMC 2021, sec. A-7).

F. PROJECT OVERMATCH

Project Overmatch is an ongoing U.S. Navy effort to create a “Naval Operational Architecture” to better link U.S. Navy and joint assess to create a more combat capable networked force. Although many aspects of this project are classified by the Navy, there are some aspects that are unclassified and can be discussed in this report, referenced from open-sourced naval statements. Project Overmatch is a part of the larger JADC2 concept that desires to create a "network that would connect numerous sensors with weapons systems, using artificial intelligence algorithms to help improve decision making" (Congressional Research Service 2021, p. 1). For the U.S. Navy, Project Overmatch is meant to enable the DMO construct where naval forces are physically distributed to avoid detection, share sensor data between units, and mass their fires at the location of their choosing. To enable the DMO construct, Project Overmatch is needed to enable the connection of naval asset data in a modern combat environment against a peer competitor. To facilitate program success, CNO Admiral Michael Gilday assigned Rear Admiral Douglas Small, Commander of Naval Information Warfare Systems Command, to lead Project Overmatch in October 2020. Rear Admiral Small was charged "to develop the networks, infrastructure, architecture, tools, and analytics that support the operational and developmental environment that will enable our stained maritime dominance." (Office of Chief of Naval Operations 2020). In this tasking memo, CNO Gilday noted that by tasking a single officer to lead this project, it would mimic previous successful naval enterprise efforts such as the Naval Nuclear Propulsion Program, Polaris Program, and AEGIS Program.

Project Overmatch has numerous implications for the development of the LDS. On a broad scale, our system design will need to utilize the communication constructs defined in both Project Overmatch and the larger JADC2 project. To enable the distributed operation of the various unmanned units of a LDS, the concepts developed from Project Overmatch will also need to be incorporated. Additionally, the use of emerging technologies identified in Project Overmatch, such as the use of AI and ML, could possibly be applied in different aspects of system design.

III. SYSTEMS ENGINEERING PROCESS

A. CONCEPTUAL FRAMEWORK FOR DESIGN

Following initial comprehension of the project tasking and review of key literature, the team broadly discussed how they envision designing the LDS. With little prior experience in practical systems engineering design, the SEA cohort 32 began project planning by referencing materials used in recent graduate course studies. Foundational to their Systems Engineering education was a general understanding of various system design process models, along with their applicability to unique system designs. Figure 3 shows a generic process model, termed the "Engineering Vee" model, which served as the basis for initial project planning, sequencing, and guidance. Of significance, the generic process described purely served as the starting point for the system design and was often modified to meet team and stakeholder needs. This process is also recursive in nature, where each step is often revisited for clarity and refinement.

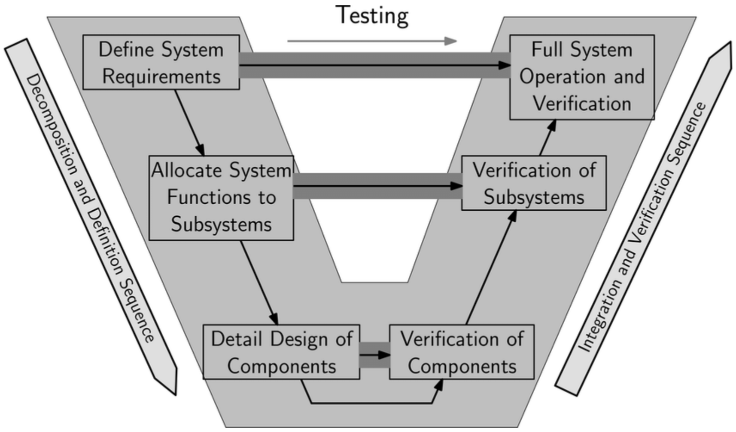

Figure 3. System Design Process Model. Source: Fabrycky and Blanchard (2011).

Beginning at the top left of Figure 3, the team would identify system requirements following stakeholder analysis and problem definition, followed by broad and focused decomposition of assessed system functions. As the functions and sub-functions become more refined, system components (unmanned platforms) would then be assigned according to the (sub)function they are capable of accomplishing, creating the system detailed design. Moving along to the right side of the Vee, the selected system components and sub-systems would then be evaluated to ensure they meet intended sub-functional requirements via performance metrics. Finally, as the sub-systems would be integrated into the whole system of systems, the team envisioned that software simulations or models would allow for appropriate evaluation (via Measures of Effectiveness) of the designed LDS. This process model was found to be influential early in the design process and provided the team with a foundation to create a more detailed project management plan, which is discussed below.

B. SEA 32 PROJECT PLAN

After the team read and digested the problem tasking and identified many of the overall design challenges, a project management plan was developed based on traditional SE guidance. Figure 4 depicts the flow of processes used, though it must be understood that the SE process is continual and iterative in nature; many aspects were revisited throughout the process to improve, clarify, or scope the problem as needed.

The left side of the graphic shows a generic timeline, consisting of progress reviews with stakeholders, culminating in a final presentation, this report, and an academic journal submission. The majority of what is seen in Figure 4 are various deliverables or subtasks that align with conceptual milestones of the project. Though not strictly adhered to, most of the deliverables and subtasks shown were addressed in a descending sequence. A color-coding sequence was also used to provide transparency to stakeholders, indicating the progress of each deliverable during progress review presentations.

The three major SE concepts used are Problem Definition, System Design, and System Analysis. In the Problem Definition portion of the project, the requirements and basic functions of this LDS are understood though analysis of the project tasking and stakeholder needs. A preliminary Concept of Operations (CONOPS) was also envisioned, along with multiple scenarios to provide a mission context for the LDS. Finally, MOEs started to be developed to provide a sense of how our eventual system would be evaluated.

The System Design phase then addresses these capability requirements, as various LDS candidates are developed which meet these needs. Initially, candidate components (platforms) of the system were rated based on their respective contribution to the system (Value System Design). Component systems are then assigned weighting factors based on specific mission contexts, contributing more or less value depending on the scenario. These candidate design alternatives are then compared against each other, where an optimal design is selected from these alternatives.

The System Analysis phase of the project then polishes the LDS's architecture allowing for detailed modeling and simulation, verification of requirements, and system validation. The CONOPS is also refined in this phase, along with a cost-benefit and risk analysis. Thorough analysis of system behavior within the context scenarios will then produce quantitative and qualitative results, yielding valuable insights which the team will relay to project advisors and stakeholders.

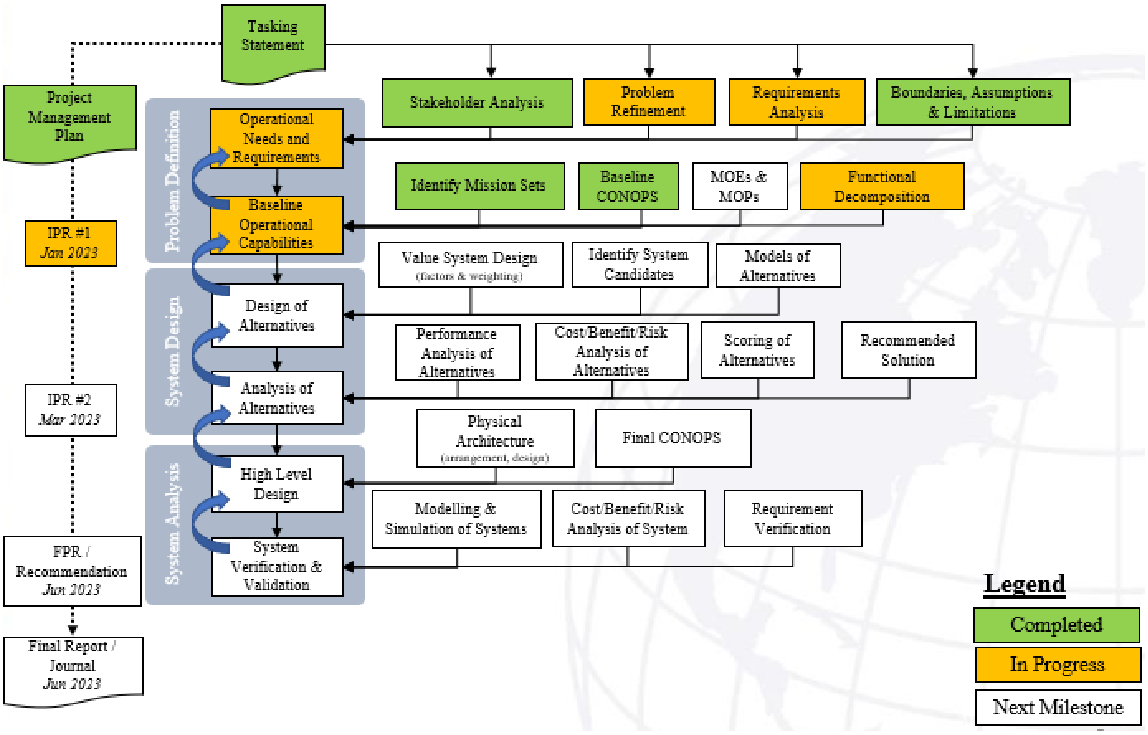

Figure 4. SEA 32 Systems Engineering Plan. Adapted from Brown et al. (2022b).

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IV. STAKEHOLDER ANALYSIS

The following contains an analysis of our tasking, a stakeholder survey, and the boundaries and assumptions arising from that analysis.

A. TASKING STATEMENT ANALYSIS

The focus of our research is to build off SEA 31's research, along with NSWI research, to engineer and analyze a multi-domain, manned-unmanned LDS. (Pollman 2022, Tab A). The tasking further specifies a non-platform centric operational concept, architecture, design, and analysis, but did not specify particular mission areas to address, instead opting for flexibility and synergy of design. It did, however, mention possible mission parameters including full spectrum Anti-Submarine Warfare (ASW), littoral strike, long range fires, port security, IAMD, grey zone activities, and protection of infrastructure. Given the encompassing nature of the assignment, the team sought a set of capabilities to accomplish as many mission areas along the competition continuum as possible while remaining resilient and flexible in system design.

The final constraint of the design was a geographical and mission dependent framework. The team was given the freedom to design the system to meet a scenario specific set of conditions. The team chose to utilize two geographically different scenarios to demonstrate the capability of the system to operate in a variety of environments, which will be further elaborated upon in part V. By choosing two different scenarios, the team will also demonstrate how the system can be instantiated depending on the threat.

B. STAKEHOLDER AND SUBJECT MATTER EXPERT (SME) QUESTIONNAIRE

Due to the encompassing nature of the tasking document, the team felt it necessary to scope the problem down to a more manageable task, which is in line with the systems engineering process. As there were many stakeholders across a variety of geographical areas, the team felt a survey would best enable a rapid scoping of the problem to facilitate meaningful work. The survey sought to determine, at the unclassified level, the opinion of high-ranking military and civilian personnel regarding the performance of various forms of platforms, concepts, hardware, and software within the next decade. The survey also asked a few directed questions about the capability of forces to act withing geographic areas or under certain conditions the team would attempt to test with modeling and simulation. The survey can be found in Appendix B.

C. ASSUMPTIONS

The stakeholder survey was instrumental in providing insight that became the basis of our assumptions moving forward. Although there was a smaller than expected number of surveys returned, and some responses were withheld due to the unclassified nature of our project, the common answers and ideas from the various stakeholders allowed the team to create and operate under the following assumptions:

1. Unmanned air and surface assets should be the primary mission platforms, with the priority of mission sets being given to strike and air denial. Ideally, strike platforms would be unmanned, sub-surface assets, or manned air assets.
2. COTS technology should be prioritized when applicable.
3. Sub-systems should be capable of withstanding the moderate usage of enemy directed energy attacks.
4. All sub-systems should be hardened, or otherwise resistant to cyber-attacks. This is especially important for unmanned platforms, which should either be hardened, difficult to hack, jam or spoof, or otherwise too numerous to effectively attack electronically.
5. Satellite Communications (SATCOM) will be generally unreliable due to the prevalence of enemy electronic attacks or attacks on the satellites themselves. The system shall be designed with alternative forms of communication and position, navigation, and timing to facilitate the use of guided weaponry.

6. The system will likely be operating in a position that is known and targetable by enemy forces. Therefore, the system will need to be designed to take damage while remaining effective.
7. Sub-systems should be capable of providing their own targeting information (active and semi-active targeting) and be capable of sharing targeting information within an interoperable network.
8. There are no expected restrictions on submerged operations apart from depth.

During the project the team realized additional assumptions would need to be made to best create a system of systems in the time given. To that end, the team decided to assume the system would be kinetic in nature. Trying to devise a system that was optimized for competition, grey zone activities, and combat was yielding infeasible results for our project timeline. The team realized that a combat system could utilize its ISR and present subsystems to perform limited competition and grey zone missions. The same was not true of a system optimized for competition or grey zone operations, thus the decision was made to create a combat system.

Likewise, the team decided to focus on COTS and kinetic technologies. Information regarding electronic warfare, directed energy, and future platforms or capabilities were not able to be found using open-source references due to their classified nature. As such, it was both unusable in our project and either blocked from our research completely or so vague as to be unusable in a model without assigning arbitrary qualities that are unsuitable to an effective model. The team determined that focusing on available, or nearly available kinetic technology, along with available or COTS platforms, was the best way forward to designing an unclassified system of system that met the objectives of our project.

To focus on comparing various capabilities brought by candidate platforms, the team chose to assume that the entirety of the system was in place for modeling purposes. This acknowledges that there will likely be a transit and deployment time associated with each subsystem and capability. However, to facilitate quicker turnaround times on modeling candidate systems, the team chose to assume that intelligence was such that the system could be prepositioned prior to the commencement of the modeling scenario.

The team also chose not to simulate land forces within the model. This was done to isolate the effects of our littoral denial system and analyze its synergy with current naval systems.

D. BOUNDARIES

As part of the systems engineering approach, the team decided to place boundaries on our system. These differ from the assumptions in that they are constraints on the system itself, and that the system was designed with these constraints in mind. They serve to keep the system realistic while also providing design goals apart from the capabilities desired by the tasking statement. Those boundaries are:

1. Time. The system will be deployable by 2033. This comes directly from the tasking statement. This limited our focus to system capabilities that were either online, or fully capable of being online within a ten-year limit. In practical terms, this means no capability below a Technology Readiness Level (TRL) of five was considered.

2. Space. As the system is a LDS, the team defined was required to define what littoral would mean for the context of the system. The team defined the littorals as 30 NM out to sea and 150 NM wide. The team derived this boundary from Milan Vego's "On Littoral Warfare." He defined it as being "areas bordering the waters of open peripheral seas, large archipelagoes, and enclosed and semi-enclosed seas. Littorals bordering open oceans, such as the coasts of North and South America, Africa, and India, extend outward to the farthest extent of the continental shelf." (Vego 2015, 4) Our self-imposed limits reflect this. 30 NM was chosen to reflect the capability of the system to interact with and support EABO operations, while also allowing EABO units to easily provide fire support for the system as necessary. 150 NM was chosen to allow sensor and fire systems to have overlapping fields of effectiveness. Additionally, the team

assessed that most littoral areas of importance, such as straits, archipelagos, or individual islands, are natural choke points and do not require the defense of expansive coastline. Therefore, we set the constraint that 150NM of system coverage will be sufficient to defend such areas.

3. <u>Cost</u>. The system will cost less than 2 DDGs, or approximately four billion U.S. dollars. This includes acquisition and Operations and Maintenance (O&M) costs. To facilitate O&M, the team has appropriated one and a half billion dollars for acquisition costs. The cost gives a reasonable budget with which to procure our system while remaining competitive with alternative solutions and allowing for O&M costs. In conversation with our stakeholders, our team assessed that the mission being considered for our system would be given today to approximately two to three Arleigh-Burke Class DDGs, as they are the primary surface asset of the navy with the firepower that our mission demands. In order to keep our system cost-competitive within an already tight military budget, our team chose two DDGs. Finally, the team could use the capabilities of two DDGs in our simulations to directly compare our system to the current littoral denial construct.

4. <u>Size</u>. Since our system must be deployable anywhere in the world, we wanted to constrain the overall size of the system. As some sub-systems are manned platforms, they will not be easily transportable and will need to be pre-positioned to be effective. However, the unmanned portions of our system not in place must meet size and weight restrictions consistent with C-17 for transportation. This will enable rapid transportation to anywhere in the world. Our system is designed to operate piecemeal as required to facilitate a variety of operations apart from full-scale.

As the project progressed, the team determined further boundaries were required. The largest was making the decision to focus on a seaborne system. The original plan was to design a land component that would operate as part of the Marine Corps EABO. The primary purpose of the land component was shore-based fires and ISR. This land component would also utilize logistics elements to efficiently resupply the system during combat. However, creating sub-systems that could be transported via L-class ships proved difficult, and the team felt that focusing on land systems detracted from surface systems that could provide more flexibility within the competition continuum.

The team also determined that designing a logistics system, while important, was not critical to the success of our project, given that the Navy already has a complex logistics system. Considering our limited budget, it made more sense to utilize what was already present and focus on innovating new combinations of COTS and unmanned technologies to pursue active littoral denial rather than resupplying our system. The tradeoff required finding subsystems that could be easily replaced or otherwise continue to function as they sustained damage.

V. MISSION CONTEXT SCENARIOS

This chapter introduces the contexts proposed for the architecture and design process for our systems of systems. Along with a brief overview of the mission context's objectives, this chapter also highlights unique features of the Gotland and Palawan scenarios.

A. MISSION CONTEXT PURPOSE

The team modified NWSI-generated fictional scenarios to aid in the system design process, specifically in identifying operational tasks. The two scenarios presented are aiding the defense of Swedish Forces on Gotland and the support of USMC EABO Forces on Palawan. The purpose of these scenarios is to make the system design process more comprehensive by introducing proposed missions to aid in identifying system functions and provide general context to the SE design process. Figure 5 shows the significant geographical differences between the two scenarios, where the island of Gotland is circled on the left graphic and the island of Palawan in circled on the right graphic. These two locations were selected for mission context scenarios as they offer challenges presented by two near-peer competitors (Russia and PRC), diverse environmental and topographical conditions, as well as varying distances to threat coastlines, introducing time constraint considerations for subsequent analysis.

Figure 5. Geographical Locations of Mission Context Scenarios

Creating a fictional military scenario can be a valuable tool when designing a military system for several reasons. First, it allows designers to explore a wide range of potential threats and challenges that may not be present in real-world scenarios. This enables them to push the limits of their imaginations and consider a wider range of possibilities for how their system may be used or tested, particularly when projecting political and technological changes ten years in the future, ensuring that the system design is robust enough to handle a variety of potential scenarios.

Second, a fictional scenario can help to eliminate biases and preconceptions that designers may have about real-world situations. When designing a system based on a real-world scenario, designers may be constrained by their assumptions about the situation, which can limit their ability to innovate or think creatively. By creating a fictional scenario, designers are free to explore new ideas and approaches without being constrained by pre-existing assumptions or biases, leading to more innovative and effective solutions.

B. GOTLAND

The initial scenario involves United States forces aiding Swedish forces to safeguard and defend Gotland, which is inherently susceptible due to its central Baltic Sea location and proximity to two Russian naval bases (Kaliningrad and St. Petersburg). The fictional backstory of the scenario is that Russia intends to invade Gotland, providing them access to a centralized port in the Baltic Sea, increase their awareness of the maritime routes to other major Baltic ports. Control of Gotland would also further their control over shipping and natural resources in the area. The goal of the mission is to discourage any Russian attack and, if required, prevent them from gaining control of the Gotland littorals by utilizing the designed LDS. Sweden and the United States are the allied forces involved in this scenario, augmented by the designed LDS. Of note, Baltic nations have also granted the United States fly-over privileges to aid in Swedish defenses. Tables 3, 4 and 5 list the force assets available for Sweden, U.S., and Russia, respectively.

Table 3. Swedish Forces for Gotland Defense Scenario

SWEDISH FORCE ORDER OF BATTLE		
NAVY	**ARMY**	**AIR FORCE**
2 Gotland Class Attack Submarines	3 Mechanized battalions	50 39 JAS C/D Gripen Fighter/Attack
7 Visby Class Corvettes	1 Air Defense battalion	4 RQ-7 Shadow UAV
	1 Artillery battalion	4 340 AEWCS 100D
	1 Logistics battalion	

Table 4. U.S. Forces for Gotland Defense Scenario

U.S. FORCES AVAILABLE FOR SURGE TO BALTIC SEA
2 Virginia class SSN
2 LCS

Table 5. Russian Forces for Gotland Invasion Scenario

RUSSIAN FORCE ORDER OF BATTLE		
NAVY	**ARMY**	**AIR FORCE**
4 Kilo class submarines	336th Marine Brigade	50 SU-34
2 Sovremenny DDG	152nd Guards Missile Brigade	15 Tu-160 Blackjack
8 Gorshkov FFGH	76th Air Assault Division	

C. PALAWAN

The second scenario involves a hypothetical conflict between the United States and China in the Philippine Sea, with a focus on protecting USMC stand-in forces on Palawan Island. The conflict begins after an armed confrontation in the South China Sea, where the U.S. sends the stand-in force to Palawan to prevent PRC from targeting U.S. bases past the first island chain. The mission in this scenario is to use the designed LDS to repel any attempts by the PRC to dislodge or neutralize the USMC stand-in forces. The system is intended to operate along the coast where the USMC forces are located during the duration of EABO. Consistent with EABO literature, the mission typically involves a contingent of 1800 to 2000 sailors and marines, including a command element, a Littoral Combat Team, a Littoral Anti-Air Battalion, and a Combat Logistic Battalion. The allied forces are the USMC Littoral Regiment and various patrolling naval assets, while the hostile forces include the PRC Army, Naval, Rocket, and Air Forces. Detailed U.S. and PRC forces are listed in Tables 6 and 7.

Table 6. U.S. Forces for Palawan Invasion Scenario

U.S. FORCES AVAILABLE FOR PALAWAN DEFENSE
(3) Arleigh Burke class DDG
1 Virginia class SSN
2 Los Angeles class SSN

Table 7. PRC Forces for Palawan Invasion Scenario

PRC ORDER OF BATTLE		
ARMY	**NAVY**	**AIR FORCE**
124th Amphib Mech Division	6 Kilo 636 SSK	50 Su-33 Flanker
144th Division	3 Renhai class cruiser	20 FC-1 Fierce Dragon
121st Infantry Division	3 Luyang class DDG	30 J-10 Vigorous Dragon
	3 Jiangkai III class DDG	50 J-11 A/C
		15 J-20 A/C
		10 Y-8FQ MMA
		2 H-6
		30 Pterodactyl UAV
		50 Soaring Dragon UAV

VI. FUNCTIONAL ANALYSIS

Functional analysis is a top-down approach that focuses on the system's overall objectives and breaks them down into more detailed functions and sub-functions. This approach is particularly useful for complex systems such as a LDS, where multiple functions and sub-functions must work together to achieve the system's objectives. The LDS is envisioned as a combination of sensors, weapons, communication systems, and will likely include air, surface, and sub-surface assets. The design of a successful LDS requires careful consideration of the system's objectives, as well as the relationships between its functions and sub-functions.

A. METHODOLOGY

Functional analysis is typically conducted in several steps, including identifying the system's objectives and requirements, breaking down the objectives into top-level functions and sub-functions, analyzing the relationships between functions, creating a functional hierarchy, and using the hierarchy to identify potential design solutions. This analysis is necessary for subsequent MOE derivation.

1. Defining the Mission and Objectives

The first step in the functional analysis process is to identify the system's overall objectives. Given the broad scope of the tasking statement, it was necessary to first define the effective need and mission that is to be achieved. Using the fictional mission context scenarios as a starting point, we defined the effective need and mission to be: *Conduct Littoral Denial Operations*

With the effective need and mission defined, it enabled the team to further define objectives, perform functional decomposition and develop a conceptual design of the system to perform analysis on. Objectives, effects, and actions are interrelated concepts in systems analysis which help to guide the planning and execution of military operations. Thoughtful deliberation of these elements ensures that the system is well designed and equipped to achieve mission success. The framework depcited in Figure 6 shows the interrelationship between the mission to be accomplished, objectives to be achieved, effects desired and actions to be taken.

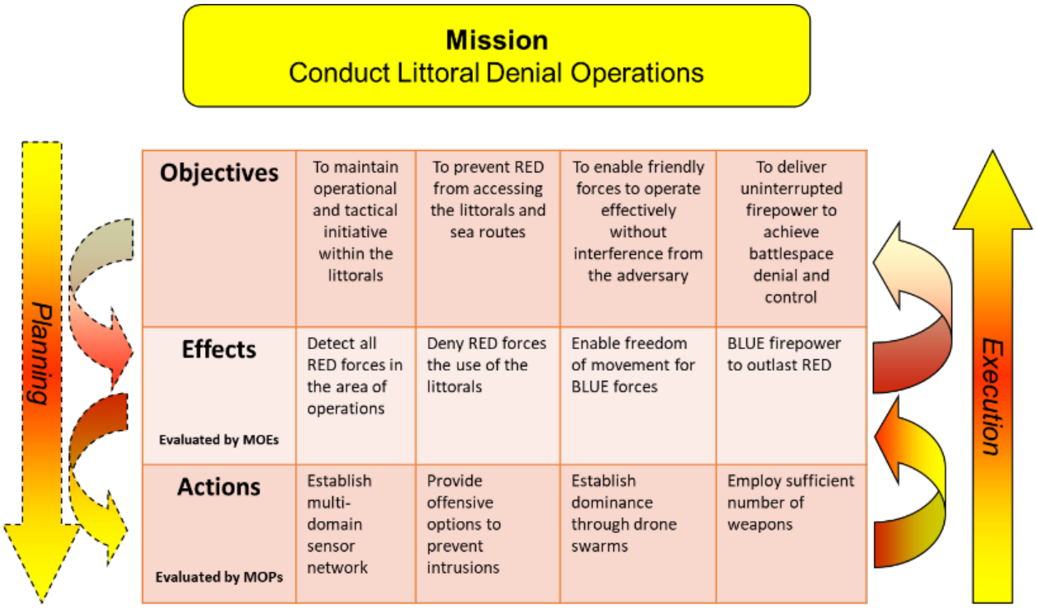
Objectives are the overarching goals or outcomes that military forces seek to achieve. They are often broad in scope and reflect the strategic aims of the military campaign or mission.

Effects are the intended or unintended consequences of military actions. They are the changes that occur as a result of military operations. Effects are what the military seeks to achieve through its actions. They are often more specific and measured by MOE.

Actions are the specific military activities carried out to achieve the desired effects. They can include offensive or defensive operations, logistical activities, or intelligence gathering, among others. Actions are how the military seeks to achieve its objectives and produce the desired effects. These are evaluated by Measures of Performance (MOP).

Based on the system's effective need and mission to *Conduct Littoral Denial Operations*, the four objectives identified were:

1. To maintain operational and tactical initiative within the littorals.
2. To prevent adversary from accessing sea routes and littorals.
3. To enable friendly forces to operate effectively without interference from the adversary.
4. To deliver uninterrupted firepower to achieve battlespace denial and control.



Objectives	To maintain operational and tactical initiative within the littorals	To prevent RED from accessing the littorals and sea routes	To enable friendly forces to operate effectively without interference from the adversary	To deliver uninterrupted firepower to achieve battlespace denial and control
Effects Evaluated by MOEs	Detect all RED forces in the area of operations	Deny RED forces the use of the littorals	Enable freedom of movement for BLUE forces	BLUE firepower to outlast RED
Actions Evaluated by MOPs	Establish multi-domain sensor network	Provide offensive options to prevent intrusions	Establish dominance through drone swarms	Employ sufficient number of weapons

Figure 6. Derivation of System Objectives, Effects and Actions

2. Functional Decomposition

To determine how the envisioned system should function, a functional decomposition was done to look at the details of *"what"* the system must do. Through this process, the critical functions of the system were identified and decomposed. Figure 7 depicts the initial functional decomposition for our system.

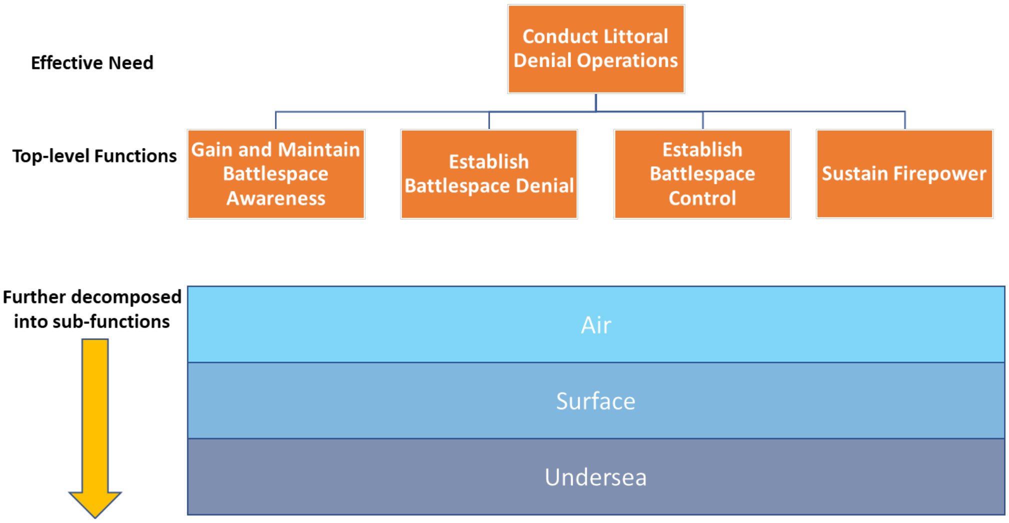


Figure 7. Functional Decomposition of Top-Level Functions

Based on the team's research, literature reviews, and stakeholder inputs, a needs analysis was conducted to determine what the DOD and services would effectively need in a LDS. The four top-level functions derived are:

1. Gain and Maintain Battlespace Awareness (GMBA). This function involves collecting and analyzing information about the environment and potential threats in the restricted area, while also maintaining situational awareness in real-time. This includes monitoring vessel traffic, environmental conditions, and other relevant factors that may impact the effectiveness of the system.
2. Establish Battlespace Denial. This function involves using a variety of methods to deny access to the restricted area, such as physical barriers, non-lethal weapons, or other deterrence measures. The goal is to prevent potential threats from entering the area, and to discourage them from attempting to do so in the future.
3. Establish Battlespace Control. This function involves using a variety of methods to establish control over the restricted area, such as by intercepting and capturing hostile vessels or personnel, or by securing and defending key locations within the area. The goal is to prevent potential threats from operating within the area, and to always maintain control over the area.
4. Sustain Firepower. This function involves ensuring that the system has a sustained capability to engage potential threats, such as by maintaining a sufficient supply of ammunition or other weapons, or by ensuring that the system can operate for extended periods of time without maintenance or repair.

These top-level functions are intended to be broad and all encompassing to ensure system versatility throughout the entire peace to war continuum. As the different warfare domains each have its own unique functional needs and characteristics, the top-level functions were further decomposed into sub-functions within the Air, Surface, and

Undersea domains. This decomposition into top-level functions and sub-functions allowed the team to analyse relationships between them and create a functional hierarchy. This functional hierarchy was useful for identifying potential design solutions and trade-offs. For example, different combinations of sensors and weapons were evaluated to determine the most effective and optimal solution. This allowed a range of solutions to be considered while ensuring traceability of all functions. Figures 8 through 10 show the team's initial functional decomposition for the sub-functions of each domain.

a. *Air Domain*

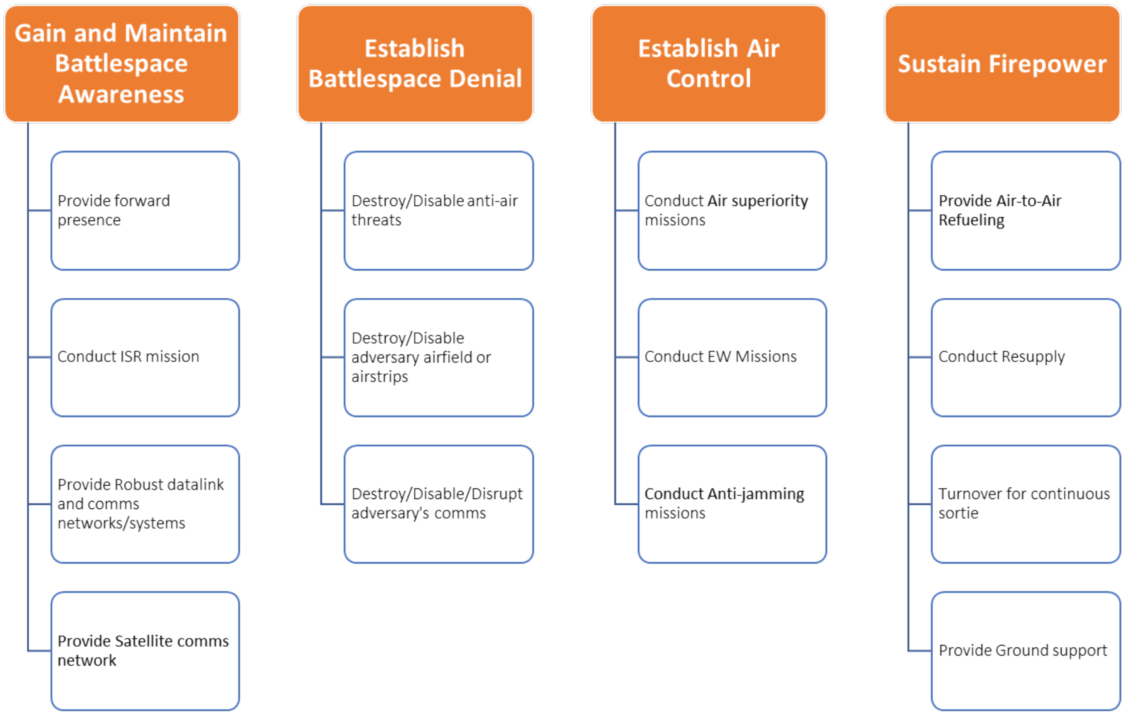


Figure 8. Functional Decomposition of Air Domain Sub-functions

The sub-functions derived for the Air domain are:

1. Provide Forward Presence. Involves positioning assets in strategic locations to ensure a persistent presence in the airspace. This provides early warning of adversary actions, as well as the ability to respond quickly and decisively to threats.

2. Conduct ISR Mission. Involves the use of ISR assets to gather information about the adversary's air operations, including their locations, movements, and capabilities. This information is used to build situational awareness and inform decision-making.

3. Provide Robust Datalink and Comms Networks/Systems. Involves the establishment and maintenance of a secure and reliable data and communications network/system. This allows for real-time sharing of information between air assets and ground stations, enhancing situational awareness and enabling effective decision-making.

4. Provide Satellite Communications Network. Involves the use of satellite-based communications systems to enable communication and data sharing between air assets and ground stations, particularly in areas where traditional communication infrastructure may not be available or reliable.

5. Destroy/Disable Anti-Air Threats. Involves the identification and neutralization of anti-aircraft threats, such as surface-to-air missiles and anti-aircraft guns, using air-to-ground weapons or other means.

6. Destroy/Disable Adversary Airfield or Airstrips. Involves the identification and neutralization of adversary airfields or airstrips, either through the destruction of the infrastructure or by rendering them unusable through other means, such as cratering the runway.

7. Destroy/Disable/Disrupt Adversary's Communications. Involves the identification and neutralization of adversary communication systems, such as radio towers or satellite uplinks, using electronic warfare or other means.

8. Conduct Air Superiority Missions. Involves the use of air-to-air weapons and tactics to gain and maintain air superiority over the adversary, enabling freedom of movement and action in the airspace.

9. <u>Conduct EW Missions</u>. Involves the use of electronic warfare assets to disrupt or disable the adversary's electronic systems, including radar, communication, and navigation systems.

10. <u>Conduct Anti-Jamming Missions</u>. Involves the use of anti-jamming techniques and technologies to ensure that air assets can communicate and navigate effectively in the presence of adversary electronic jamming.

11. <u>Provide Air-to-Air Refueling</u>. Involves the provision of mid-air refueling capabilities to enable air assets to remain in the airspace for extended periods, enhancing the persistence and effectiveness of air operations.

12. <u>Conduct Resupply</u>. Involves the provision of ongoing logistical support, including fuel, ammunition, and other supplies, to ensure that the system continues to operate without interruption.

13. <u>Turnover for Continuous Sortie</u>. Involves the rotation of air assets to ensure that they remain available and effective over extended periods. This allows for continuous operations and avoids the risk of overworking and degrading the air assets.

14. <u>Provide Ground Support</u>. Involves the provision of ground support equipment and personnel to ensure the safe and effective operation of air assets. This includes maintenance, repair, and other support services.

b. Surface Domain

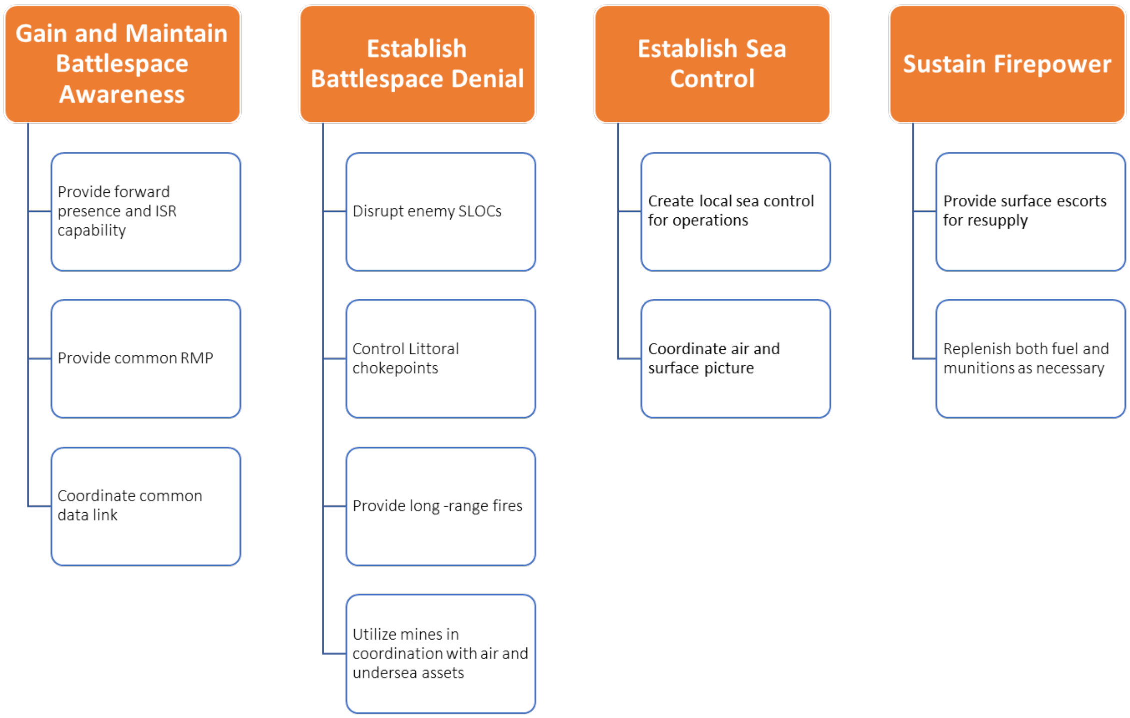


Figure 9. Functional Decomposition of Surface Domain Sub-functions

The sub-functions derived for the Surface domain are:

1. Provide Forward Presence and ISR Capability. Involves deploying air and surface assets to gather ISR data on potential adversaries. This could involve using various sensors and platforms, such as UAVs, manned aircraft, and surface ships, to conduct overwatch and monitoring of the operational area.

2. Provide Common RMP. Involves the establishment of a common Reference Mission Profile (RMP) for all air and surface assets operating in the littoral area. This would ensure that all units are operating on the same page, with a shared understanding of the overall mission objectives and priorities.

3. Coordinate Common Data Link. Involves ensuring that all air and surface assets are using a common data link to communicate with one another and share information. This would help to avoid confusion and facilitate more effective coordination of operations.

4. Disrupt Enemy SLOCs. Involves disrupting or denying the use of Sea Lines of Communications (SLOCs) by potential adversaries. This could involve the use of mines, submarine warfare, and other tactics to make it difficult or impossible for enemy vessels to move through the littoral area.

5. Control Littoral Chokepoints. Involves establishing control over key chokepoints in the littoral area, such as narrow straits or channels, to limit the movement of potential adversaries. This could involve using surface ships, mines, and other assets to monitor and control these chokepoints.

6. Provide Long-Range Fires. Involves the use of long-range precision fires to deny or disrupt potential adversary movements in the littoral area. This could involve using land-based artillery, naval gunfire, or air-launched missiles to attack enemy targets from a distance.

7. Utilize Mines In Coordination With Air and Undersea Assets. Involves the coordinated use of mines, both bottom and moored, in conjunction with air and undersea assets to create an effective area-denial capability. This would involve the use of minesweeping assets and surveillance to ensure the safe movement of friendly forces.

8. Create Local Sea Control for Operations. Involves establishing control over the local sea space to enable friendly operations. This could involve the use of surface ships to monitor and control the area, as well as the use of aircraft and other assets to provide overwatch and support.

9. Coordinate Air and Surface Picture. Involves ensuring that all air and surface assets are working together to establish and maintain a comprehensive picture of the operational area. This would involve sharing

data and coordinating operations to ensure that all assets are working together effectively.

10. Provide Surface Escorts for Resupply. Involves using surface ships to escort resupply vessels to ensure their safe arrival at the destination. This would involve coordinating with air and undersea assets to provide effective overwatch and protection.

11. Replenish Both Fuel and Munitions As Necessary. Involves the use of Underway Replenishment (UNREP) to provide both fuel and munitions to air and surface assets as needed. This would involve coordinating with other assets to ensure that UNREP operations can be conducted safely and effectively.

c. Undersea Domain

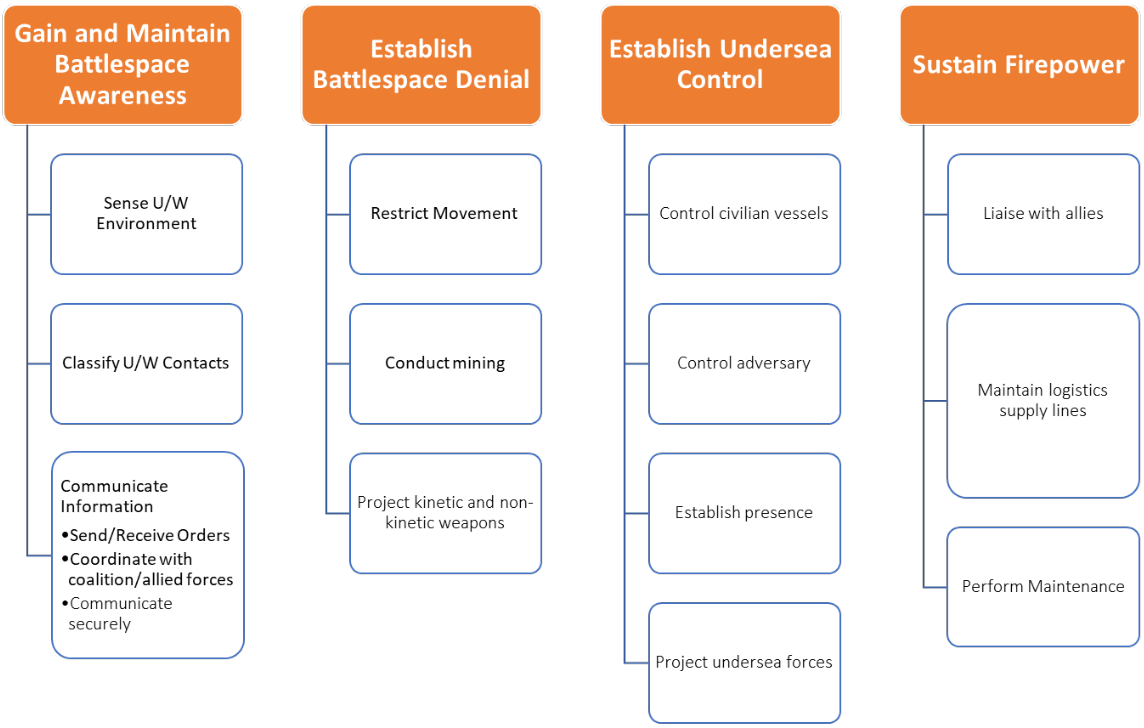


Figure 10. Functional Decomposition of Undersea Domain Sub-functions

The sub-functions derived for the Undersea domain are:

1. Sense U/W Environment. This sub-function involves utilizing various sensors and systems to gather information about the undersea environment, such as water depth, temperature, and salinity. This information can be used to support other sub-functions, such as detecting and tracking undersea contacts.
2. Classify U/W Contacts. Once a contact is detected, this involves analyzing the data collected from sensors to determine the identity and characteristics of the contact, such as its size, speed, and direction.
3. Communicate Information. Involves the secure transmission of information gathered about the undersea environment and contacts to other assets. It also involves coordinating with other friendly forces operating in the environment to share information and collaborate on operations.
4. Restrict Movement. Involves using undersea assets, such as mines or barriers, to restrict the movement of adversary ships or submarines in key areas.
5. Conduct Mining. This involves deploying mines in strategic locations to disrupt or deny adversary movement.
6. Project Kinetic and Non-Kinetic Weapons. Involves using undersea assets to project kinetic weapons, such as torpedoes, or non-kinetic weapons, such as electronic warfare, to deny or disrupt adversary operations.
7. Control Civilian Vessels. Involves monitoring and controlling civilian vessels operating in the undersea environment to ensure their movements do not interfere with military operations.
8. Exert Control Over Adversary. Involves using undersea assets to exert control over adversary ships or submarines, such as the use of torpedoes or other weapons systems.

9. Establish Presence. Involves deploying undersea assets to establish a persistent presence in key areas of the undersea environment.

10. Project Undersea Forces. Involves using undersea assets to project military power, such as by deploying special operations forces or other assets.

11. Liaise With Allies. Involves coordinating with allies and coalition partners to ensure a coordinated approach to sustaining the LDS.

12. Maintain Logistics Supply Lines. Involves maintaining the logistics supply lines necessary to keep undersea assets operational, such as using resupply ships or submarines.

13. Perform Maintenance. Involves performing maintenance on undersea assets to keep them operational and ready to conduct missions.

3. Defining Measures of Effectiveness (MOEs)

The MOE is a metric used to evaluate the effectiveness of military operations and the attainment of objectives. It is a metric which provides a quantitative means of assessing progress towards objectives and allows commanders to make informed decisions based on the performance of the candidate systems. By selecting appropriate MOEs, we can evaluate key aspects of the system and determine whether the overall design is effective. MOEs can also be used to provide feedback which then allows the project team to fine-tune the performance of the system. Figure 11 shows the four selected MOEs, along with their performance evaluation measures, as they pertain to each of the major system functions.

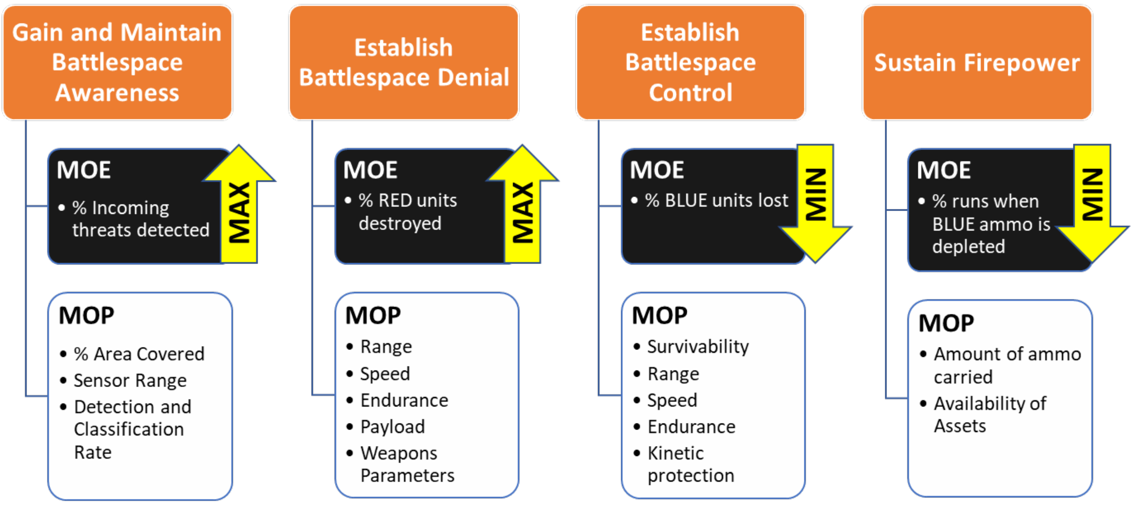


Figure 11. Derivation of System MOEs

For the gaining and maintaining of battlespace awareness, the aim would be to sense all hostile threats that enter the multi-domain battlespace. Hence, the MOE selected is the **percentage of all incoming threats detected within a specified time period**. As percentage of threats detected increases, it indicates that BLUE forces have a better awareness of the battlespace which would then provide it with a decision advantage.

For the establishment of battlespace denial, the aim would be to "deny" hostile units the usage of, as well as mobility within the battlespace. As it is difficult to evaluate this aim quantitatively, the team selected **percentage of RED units destroyed** as a proxy metric to evaluate the system's performance in denying battlespace usage. As more RED units are killed, then BLUE's ability to deny the area to RED is said to have increased.

The idea of battlespace control refers to the strength of the navy within the area of control. When the navy is said to have control over the area, it implies that it dominates the battlespace ensuring that its own forces and allies have the freedom of movement within the battlespace. It also implies that it is so strong that hostile threats cannot attack it. To this end, the MOE selected to quantify this is the **percentage of BLUE units lost**. As more BLUE units are lost, then the level of battlespace that BLUE controls is said to be diminished.

The idea of sustaining firepower is to determine how often the system would run out of resources first when pitted against RED force. In deriving the MOE, the project team set the assumption that there would be no resupply. This is to reduce the complexity of modeling such a scenario. To that end, the MOE selected to quantify this is the **percentage of simulation runs when BLUE ammunition is depleted**. This models the probability of BLUE ammo being depleted first, when compared against RED.

B. CONCEPT OF OPERATIONS

As seen in the CONOPS (Figure 12), the team's refinement process scoped the problem to design a primarily kinetic system that is seaborne but retains the ability to network with inorganic systems such Marine EABOs ashore. The system shall also be capable of networking with current naval platforms that are in inventory or approaching Initial Operational Capability (IOC). Additionally, the various subsystems may be employed individually or piecemeal to achieve effects oriented toward competition or grey zone activities.

For ISR, the team has identified a capability similar to that of a sail drone, to best provide picket sensing. The intent of picket sensing is to place outlying sensors to identify distinctive enemy signatures, either electronic, or acoustic, and relay them within the mesh network. The sail drones we based this capability on are small, maneuverable, and solar powered. This allows them to endure as long as the mission requires without being resupplied. They can blend in with regular surface traffic while reporting signatures of interest. They are also relatively inexpensive, costing thousands to tens of thousands of dollars per platform. This allows the system to field a large number and seed an area with overlapping search fields. In the future, they may also provide real time imagining, but the necessary equipment to provide that capability currently would render such a picket force more expensive and reduce their capability to cover a large area while remaining attritable.

For kinetic fires, a combination of lightly manned and unmanned surface and air platforms is envisioned to provide a unique capability to keep the man in the loop for fires while reducing the risk to manned forces. While it is possible to utilize unmanned platforms to fill the fires role, providing a combination of manned and unmanned platforms enables a commander to operate in various levels of combative risk while retaining the flexibility to automate as the situation demands. To fulfill the fires function, we identified several capabilities to include lightly manned platforms, missile barges, Navy USVs and UAVs, USVs like those used to sink *Moskva,* and semi-submersibles.

Finally, UUVs will provide ISR, mine laying and reseeding, and fires. The UUV capability provides a commander the flexibility to remain covert in gathering information or preparing a battlespace in a way that surface or air platforms cannot. Using UUVs does require additional reliance on unmanned platforms as it is assumed that communications with headquarters are unable to be maintained throughout their mission. To utilize this capability to the fullest, some long held conventions on unmanned platforms will need to be reexamined.

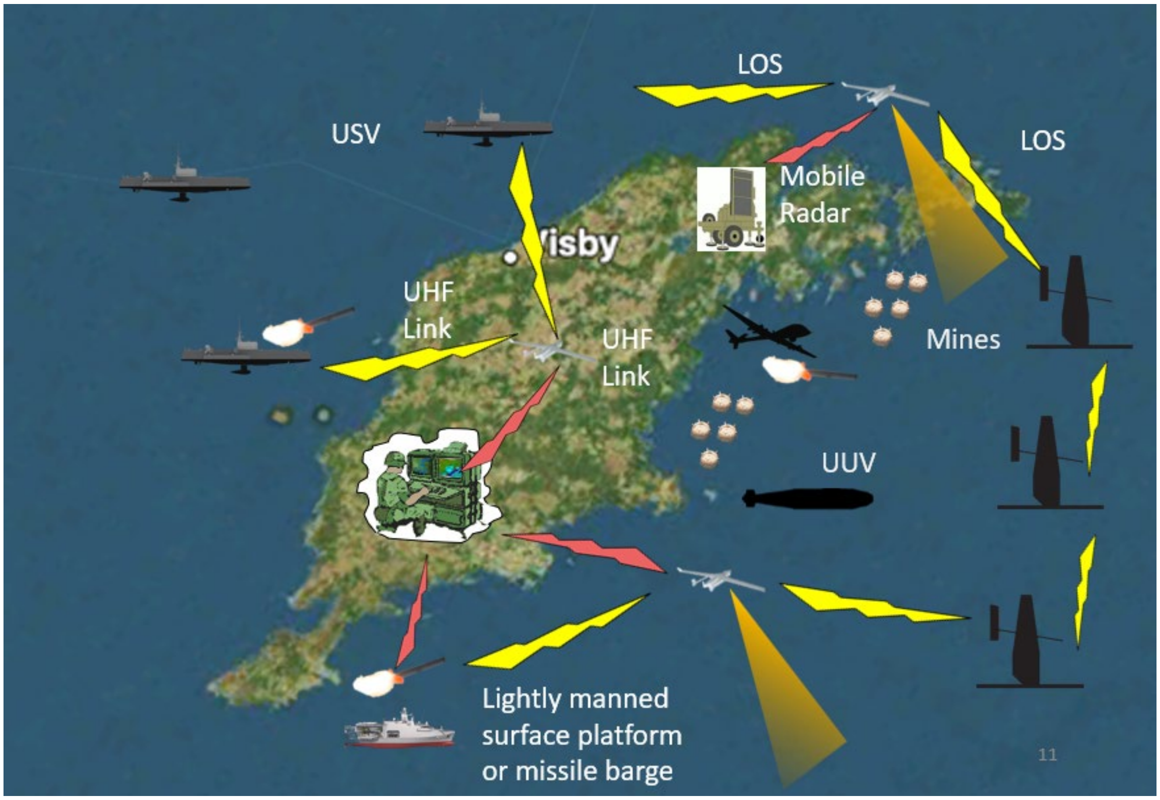


Figure 12. Proposed CONOPS Centered on The Island of Gotland

In support of the proposed CONOP, our team has developed the following communications architecture. We focused on surface and air communications as undersea assets typically spend extended periods of time out of communications. As a result, it relies on mesh networking with a combination of UHF/VHF Line of Sight (LOS), HF, and SATCOM. This was done to minimize the chance of jamming or otherwise using electronic attack or interference in any one spectrum. This is sufficient to transmit signals and emissions data from both manned and unmanned platforms, as well as low resolution video, and is compatible with current communications in use by the fleet. In the event of compromised communications due to hostile actions or unforeseen technical issues, HF will act as a backup EHF SATCOM as the emergency source. HF will prevent video transmission, reducing targeting fidelity from unmanned platforms. EHF SATCOM was chosen as a tertiary communication plan since it is the most secure satellite connection. While we are expecting satellite communication to be denied, or the satellites themselves destroyed, it is probable that a contingency plan will be created to enable limited SATCOM use.

Communication range is a function of a variety of factors, to include transmitter power, transmitter and receiver gain and loss, antenna temperature, the frequency wavelength, and the required Contrast-to-Noise Ratio (CNR) and link margin. The link margin indicates the excess CNR achieved by the system and helps with providing a buffer to various attempts at disrupting communication. The final formula for total communications range with the following component requirements is shown below (Harney 2013, 194–195):

Component Values and Requirements

P_T	Transmitter Power
G_T	Transmit Antenna Gain
L_T	Transmit Loss
L_A	Atmospheric Loss (rain)
L_R	Receive Loss
G_R	Receive Antenna Gain
T	Antenna Temperature
B	Bandwidth
R	Range
F	Noise Figure
k	Boltzmann Constant
$16\pi^2$	Constant
λ	Wavelength (20 GHz)
CNR_R	Required CNR
LM_R	Required Link Margin

$$R = \left[\frac{P_T G_T L_T L_A G_R \lambda^2}{KTBF16n^2 CNR_R} \right]^{1/2}$$

While the formula for the horizon limitation of communications where H is the antenna height is (Harney 2013, 194–195):

$$L(km) = 4.122H^{1/2}$$

UHF, as a line-of-sight communications system, is the primary point of limitation within our communications architecture as it does not bend with the horizon without large amounts of atmospheric ducting. Therefore, our communications range is primarily limited by the power used to generate communications, as well as the antenna height. Utilizing UAVs will result in less platforms required for communications coverage, with the tradeoff being that the antenna locations are more known, making these platforms more targetable. Using USVs or sail drones requires more vessels due to the smaller range but allows for potentially more covert nodes. HF and EHF typically require more power and will be concentrated in larger vessels and UUVs, with the smaller platforms retaining the capability to receive those transmissions.

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VII. UNMANNED PLATFORM REVIEW

With unmanned platform systems being a significant contributor to our LDS, the team conducted a comprehensive open-source review for unmanned systems across all domains. Due to the unclassified nature of our project and research, the team was limited in the complete understanding of each platform and its associated capabilities. However, some common parameters were available that would provide a simplified foundation for follow-on analysis, including platform speed, fuel type, endurance, altitude (or depth), weapon employment, generic sensor types and communications equipment, cost, etc. For those platforms that provided some, but not all, of the above parameters, reasonable estimates were assumed through comparisons with similar platforms and technologies. This data was then compiled for utilization in the Value System Design and candidate system generation and optimization tools. Brief platform summaries are provided below.

A. AIR PLATFORMS REVIEW

The air domain team was tasked with working both on the functionalities that the system should perform in the air domain and on the range of air platforms that should be considered for analysis of alternatives. Regarding air platforms, the primary emphasis was placed on ensuring adherence to the tasks and sub-functions associated with each top-level function, such as gaining and maintaining battlespace awareness, establishing battlespace denial, establishing battlespace control, and sustaining firepower. Following the literature reviews, another aspect was considered to focus on selecting platforms that pose minimal risk to the allied forces and which were less vulnerable to attacks. Consequently, only unmanned platforms were evaluated as they possess scattering capability without detection, reducing the possibility of being targeted and destroyed. Moreover, deploying unmanned platforms enables the allied servicemembers to remain outside conflict zones, reducing the risk to human life, making unmanned options a more feasible and cost-effective long-term option.

The final factor considered was the platform’s maturity level. Although it is preferable to have the latest technological advancements, the system must be operational within a ten-year timeframe, which is a significant constraint. Therefore, based on a thorough analysis of past market trends, the team concluded that the maturity level should be limited to TRL7 to meet the imposed requirement. Considering all these factors, a roster of unmanned aerial platforms was compiled and incorporated into the optimization model along with platforms from other domains. To conduct this comprehensive survey, open-sources internet publications and manufacturer provided data were utilized, given the ostensive nature of these sources for an unclassified project.

B. SURFACE PLATFORMS REVIEW

In considering platforms for the surface domain, the team sought to prioritize presence and synergy with ashore units. This was done to enable long-range fires and local sea control functions. As disrupting sea lines of communication and generally providing denial can be accomplished through a variety of platforms, we chose to give them less priority. Finally, we wanted to ensure that mines were given due consideration due to their cost and ability to control choke points without the need for support. While the undersea team was also examining mines, we wanted to consider surface deployed mines, or mines that are tethered at or near the surface. Since we were examining different functions from the undersea team, it seemed we may have been able to find a use for mines where they could not.

The team also understood that the manned portion of the manned/unmanned system would likely be found in the surface domain. UAVs are already in use in every branch of the military, and it is unlikely that a manned air platform would be capable of operating within our budget. Additionally, undersea platforms are expensive to purchase or design. However, manned surface platforms can take on a variety of forms that would lend themselves to the littorals. Our team spoke with NPS professor Dr. Shelby Gallup and became intrigued with his LMACC (Lightly Manned Autonomous Combat Capability) design. The system is designed with approximately fifteen people in mind and optimized for the role of light combat craft. Its firepower in relation to its size lent itself to our project and was the largest manned craft we considered.

Finally, for unmanned craft we split our focus along two lines of effort. The first was the standard USV. We assessed the capability of the Navy's USVs, a USMC design, as well as those in use by Ukraine in its conflict with Russia. We also focused on a few unconventional ideas, one of which was the missile barge. The idea would be to utilize cargo to carry Vertical Launch System (VLS) or missile cannisters and fire from third-party targeting. The vessels would be cheap to acquire and can theoretically carry more missiles than traditional platforms. They could then be floated or anchored in the vicinity of expected action and provide a mobile missile battery with which to conduct air defense or surface fires without the possible loss of personnel or ships that could be better used elsewhere.

C. UNDERSEA PLATFORMS REVIEW

The undersea domain team performed similar searches for undersea platforms for use in the LDS, to include UUVs, mines, and sensors. However, the team encountered difficulties in obtaining reliable information for most of the platforms due to the classification levels that are inherent to most of these assets. Platform descriptions and general information were available through most of their manufacturer's websites; however, performance characteristics and capability details were often not advertised. Accurate financial estimates were also difficult to find over open-source references. To circumvent these obstacles, the team relied on comparisons of similarly sized and capable platforms, along with their manufacturing specialties. As a result, numerous assumptions were made to produce an adequate list of undersea platforms for subsequent analysis and use in the optimization program.

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VIII. VALUE SYSTEM DESIGN AND SCORING

A. VALUE SYSTEM DESIGN CONCEPT

Each domain team was responsible for the Value System Design for all potential unmanned platforms in their domain. Across all domains, however, a rating scale from 0–10 was used to standardize the values that would eventually be used in our optimization program. Each platform was compared against all others and assigned a value for the following capabilities: Sensor type and its advertised maximum detection range, weapon types and their associated lethality (range, damage potential, speed, etc.), as well as its advertised maximum speed, depth (or altitude), and endurance. We also assigned values based on known (or assumed) individual platform cost and Technical Readiness Levels.

While some platforms were ranked or valued differently due to unique capabilities, the majority of platforms and associated capabilities were rated using one of the three methods illustrated in Figure 13. For example, to assign a speed value to a UAV platform, we would use a linear method illustrated by the graph on the left. Here, the fastest UAV would receive a ten, associated with its advertised speed value. Then a zero would be assigned to any theoretical UAV with 0mph. From there, each of the remaining UAVs would be assigned a linearly interpolated value based on where its advertised speed would fall between 0mph and the speed of the fastest UAV.

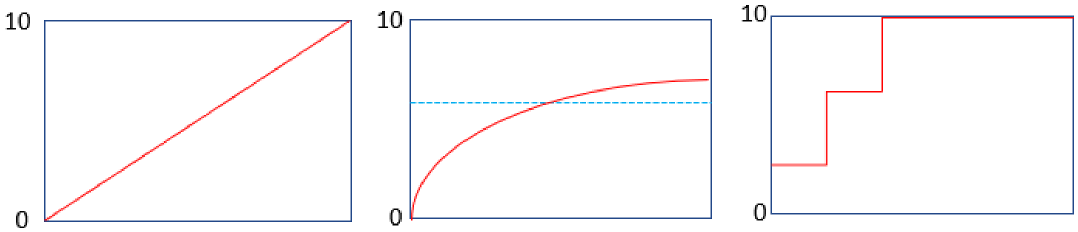

Figure 13. Value Scoring Methods

The center graph illustrates situations where exceeding a designated performance capability provides no additional value to our system. For example, if the maximum water depth in a certain area is only 1,000m, then UUV platforms with advertised depth capabilities of 4,500m will not be rated higher than ones with 1,000m.

Finally, the graph on then right illustrates performance parameters that were ranked in "value tiers." This is the method we chose to evaluate endurance capability, where platforms with endurance greater than or equal to six months (the assumed mission operating time) would be assigned a score of ten, platforms with endurance between three and six months were assigned a slightly lesser value, and so on.

The TRL value was assigned based on its current assessed TRL. With the time limit of ten years for technological maturation, we assumed that any potential platform with a TRL of five or less would not be sufficiently available for our system, received a score of zero, and was no longer considered for candidate system integration.

The platform performance ratings then influenced their subsequent "Functional Score," where certain performance parameters were combined to yield an effective rating to the platform's contribution to a specific system function. For example, for GMBA in the undersea domain, the individual platform's performance rating for Speed, Sensor Capability, and Depth were averaged. Similarly, a platform's contribution to the "Battlespace Denial" function consisted of the averaged scores for the platform's weapons capabilities (if it existed), and Speed. This process was performed for all platforms in all domains, providing a foundation of rated candidate platforms for use in our system of systems. Results for the scoring of all these systems can be found in Appendix C of this report.

B. AIR DOMAIN VALUE SYSTEM DESIGN SCORING

1. MOP Value Scoring

This Section describes the performance value scores for the evaluated aerial systems, including why these MOPs are important to system design and how each was scored. The evaluation of MOPs is critical when comparing different platforms. MOPs are performance metrics that enable a quantitative and objective assessment of a platform's performance, measuring its ability to achieve its intended goals and objectives. This approach helps identify the strengths and weaknesses of each platform and forms a basis for comparing different platforms. Evaluating MOPs is crucial in identifying the most effective and efficient platforms that meet various operational requirements, thus ensuring system capability to achieve its mission while optimizing resources and reducing risks. These MOP value scores are then used to evaluate overall platform scores as they pertain to system functions.

a. Speed, Weight, Range and Endurance Scoring

To facilitate coherent comparisons, aerial platforms were subdivided into six different mission categories. This was necessary to avoid comparing, for example, the speed score of an aircraft performing an air defense mission with one conducting ISR. These missions require different speeds, and therefore, require different formulas for grading the platforms. For instance, each aircraft category used a range of speeds that corresponded with its specific mission to be graded. By following this approach, the developed optimization model could compare different platforms more equitably. This method ensured that the platform with the best performance was selected, considering the restriction of fulfilling all the designated functionalities.

To demonstrate how the grades were assigned, let’s first consider the metric used to measure the aerial platforms altitude score. The platforms were evaluated based on their altitude capacity using the maximum operating ceiling data, which was used to assign grades on a scale from zero to ten. The assigned grade depended on the expected maximum ceiling for the particular type of aircraft. It should be emphasized that it is crucial to prevent aircraft that exceed the maximum expected ceiling for their platform from receiving a grade above 10 on the scale utilized. Below is a description of the mathematical formula used in the excel table:

$$Altitude\,Grade = MIN\left(10; \frac{Platform\,Max\ Altitude}{Max\,Expected\ Altitude} \times 10\right)$$

The same methodology described for grading the altitude score was used to assign degrees from zero to ten for speed, weight, range, and endurance scores. Similarly, each of these different MOPs referenced the maximum expected performance value for the specific mission category.

b. Weapon Scoring

To evaluate the platforms' weapon capacity, a different approach was used. The Air warfare team established a scale of zero to ten based on the type of kinetic capability. If a platform lacked weapon capacity, it received a score of zero, while a platform with grade ten capability should be able to use various types of airborne weapons, including laser-guided bombs, medium-range and Beyond Visual Range (BVR) missiles, and missiles with hypersonic technology. However, due to the minimum expected platform maturity level, none of the platforms evaluated were able to achieve a grade ten rating in terms of kinetic power. Below is a brief overview of how the platforms were graded.

$$\textit{For systems with no weapons} : \textit{Weapon Score} = 0$$

$$\textit{For systems with laser guided bombs and medium} - \textit{range missiles} : \textit{Weapon Score} = 6$$

$$\textit{For systems with laser guided bombs and long} - \textit{range missiles} : \textit{Weapon Score} = 7$$

c. Fuel Type Scoring

The team evaluated various aspects, including availability, price, sustainability, and efficiency, to assess different aerial platforms based on the type of fuel used. The platforms were graded on a scale of zero to ten, with the highest grade given to air platforms that had a theoretical unlimited source of energy to sustain their operations. Consequently, the highest degrees are related to renewable energy sources, allowing greater flexibility for platforms and reduction in operating costs. The following shows how each air platform's energy source was rated:

$$\textit{For systems using heavy fuel oil} : \textit{Fuel Type Score} = 4$$

$$\textit{For systems without petroleum derivatives with high performance additives} : \textit{Fuel Type Score} = 5$$

$$\textit{For systems with hybrid power} : \textit{Fuel Type Score} = 8$$

$$For\ systems\ without\ \ fuel\ required: Fuel\ Type\ Score = 10$$

d. Sensor Scoring

To grade the platforms regarding their sensor capabilities, the team again had to arbitrarily set a grade on a scale ranging from zero to ten, based on their ability to accommodate different sensors. If a platform was incapable of carrying sensors, it would receive a score of zero. On the other hand, a platform that could support various sensor types would receive the highest score on the scale. Below is the scoring system used:

$$For\ system\ with\ no\ Sensor\ capability: Sensor\ Score = 0$$

$$For\ EO / IR / SAR\ \ capability: Sensor\ Score = 5$$

$$For\ EO / IR / SAR / ESM\ \ capability: Sensor\ Score = 7$$

$$For\ \ EO / IR / SAR / SIGINT\ / COMINT\ capability: Sensor\ Score = 8$$

$$For\ RADAR / EO / IR\ \ capability: Sensor\ Score = 9$$

$$For\ RADAR / EO / IR / COMINT\ capability: Sensor\ Score = 10$$

e. TRL Scoring

The level of maturity of the development platform under consideration was determined based on the TRL specified by the manufacturer or available in specialized publications. The team then established a staggered ranking system, considering the TRL. It is important to mention that any platform with a TRL below 5 was deemed incapable of operating over a ten-year period and would be assigned a score of zero. Below is an explanation of the ranking system implemented by the team.

$$For\ system\ with\ TRL\ 5\ or\ less: TRL\ Score = 0\ .$$

$$For\ system\ with\ TRL\ 6: TRL\ Score = 6$$

$$For\ system\ with\ TRL\ 8: TRL\ Score = 7.5$$

$$For\ \ system\ with\ TRL\ 9 : TRL\ Score = 10$$

2. MOE Value Scoring

It is also necessary to discuss the process for calculating the overall MOE value score for the aerial systems based on the previously calculated MOP scores. These MOE value scores are related to the overall system functions and MOEs as previously discussed. All these MOE metrics were then standardized on a scale of 0 to 10.

a. Air GMBA Score

To calculate the GMBA system function score for aerial domain, the altitude, speed, and sensor MOP scores were considered. The peculiar nature of the aerial environment means that sensing ability is not solely dependent on the type of sensor used, but also on the altitude at which the system is operating. Additionally, speed plays a crucial role in these calculations, as systems with higher speeds are more efficient in searching the area and maneuvering to utilize their sensors effectively. All three MOP scores are equally important in the GMBA function, and the following Equation was used to determine the GMBA score for air platforms, equally weighing altitude, speed, and sensor factors into an overall score.

$$GMBA\ Score = \frac{Altitude\ Score + Speed\ Score + Sensor\ Score}{3}$$

b. Air Denial Firepower Score

To calculate the MOE value score for the denial system function in air warfare systems, the altitude, speed, and weapon score were taken into consideration. In contrast to the GMBA score, the denial score was heavily reliant on the weapons score MOP value, and if the system being evaluated scored 0 for the weapons score due to a lack of weaponry, the denial score would also be 0, as it would not possess the ability to prevent the enemy from utilizing the aerial environment. However, when the weapons score was greater than zero, the altitude and speed scores were factored in to determine the denial score, acknowledging the advantages that altitude and speed provide in utilizing aerial weapon systems. Therefore, the Equations used to calculate the denial MOE value score are as follows:

$$\begin{gathered} If\ Weapon\ Score = 0,\ Denial\ Score = 0; \\ Else\ Denial\ Score = \frac{Altitude\ Score + Speed\ Score + Weapon\ Score}{3} \end{gathered}$$

c. Air Control Firepower Score

In the context of this system, control refers to a system's ability to survive in a combat environment, and for aerial systems, the MOP value scores of altitudes, speed, and weight are considered when calculating the MOEs. In the case of the control MOE for aerial systems, speed, and depth were significant factors to consider since they impacted a system's ability to avoid being targeted. Additionally, weight was another MOP factor that was evaluated during domain discussions as larger systems were deemed to be more survivable. To incorporate the weight score into the control score, the inverse of the calculated weight score was utilized in the Equation. Based on this assessment, the following Equation was formulated for the overall control score:

$$Control\ Score = \frac{Altitude\ Score + Speed\ Score + \left(10 - Weight\ Score\right)}{3}$$

d. Air Sustain Firepower Score

The purpose of calculating the "sustain" firepower function score for the aerial domain was to assess the platform's firepower sustaining portion, which accounted for the MOP scores for weight, fuel type, and endurance. Weight was an essential factor to consider in sustainability, as larger systems generally require more logistical and maintenance resources. The fuel type scores were also considered, as they affect the required infrastructure for the system and ultimately impact sustainability. Furthermore, endurance scores played a crucial role in the calculation of the aerial sustain firepower score, as systems with higher endurance were deemed to be more sustainable as combat systems since they required less supporting infrastructure to operate. All three MOP value scores were given equal weight in the following Equation for sustain firepower scores:

$$Sustain\,Firepower\,Score = \frac{Weight\,Score + Fuel\,Type\,Score + Endurance\,Score}{3}$$

C. SURFACE DOMAIN VALUE SYSTEM DESIGN SCORING

1. MOE Value Scoring

Since surface platforms carry a wide variety, and often multiple types, of sensors and weapons onboard, the surface team decided to simplify the metrics we would use to rank platforms. To do this, we only considered the most capable sensor and weapon onboard the vessel.

a. SUW GMBA Score

For the GMBA score, the surface team considered the sensor with the longest advertised range onboard each candidate platform. The sensor with the longest range was assigned a value of 10, and each candidate platform was normalized from that value using the following formula.

$$\frac{Candidate\,value}{Maximum\,value} \times 10$$

While some sensors are optimized for specific threats, the team did not want to assign surface candidate to each threat as that would constitute a platform centric approach. Instead, the sensor with the greatest capacity was delineated to facilitate choosing the capability instead.

b. SUW Denial Score

To determine a denial score, the surface team sought to use explosive pounds of TNT as the defining metric. While that eliminates choosing candidates based on their electronic attack capabilities, it was in keeping with the assumptions and constraints listed earlier. Pounds of TNT was chosen because it is a standard measure for explosive force and thus could be calculated for every weapon capability, ensuring we did not have to assign subjective value to weaponry. Again, a normalization method was used with the maximum pounds of TNT available to a candidate weapons system assigned a 10.

c. SUW Control Score

This value was more difficult for the surface team as there was not a standard metric like range or pounds of TNT. Armor was considered, but the lack of armor on most platforms due to modern weaponry made it insufficient. Stealth, or radar absorption capability, was also considered. However, it was not prevalent on most ships and so it was again considered insufficient. Finally, a formula was developed to determine a control metric which was based on the ability of the candidate platform to defend itself. Platforms designed for attrition such as weapons or suicide drones carried a score of zero. That formula was:

$$Control = \frac{1}{Radar\,Cross\,Section} + number\ of\ defensive\,engagements\ at\ one\,time$$

This formula served to allow small vessels or vessels with a low freeboard to be compared to vessels with a large amount of point defense weapons. Finally, the numbers were normalized.

d. SUW Sustain Firepower Score

For surface sustainment, the team examined the amount of ammunition carried and the number of days a platform could stay at sea without refueling. If either of these two metrics were exceeded, the platform would be unable to fight. Combining the two metrics into one score allowed sensing candidates to be directly compared to combatants. To achieve this, each score was normalized individually and then added together. For example, comparing a sail drone to the LMACC would result in the following:

$$Sail\ drone = normalized\ endurance\,score + 0\left(it\ has\ no\ weapons\right)$$

$$LMACC = normalized\ endurance\,score + normalized\ weapons\,score$$

D. UNDERSEA VALUE SYSTEM DESIGN SCORING

Due to the complexity of the underwater environment and the vehicles that operate in that region, a somewhat complex value system design for underseas systems was developed by the undersea domain team. Like the other groups, values scores were first created for the MOPs and then those scores were combined to make an overall MOE score for each system. The ways that these MOE and MOP scores were created are explained in this Section.

1. MOP Value Scoring

In this Section, the basic MOP value scores are described for the underwater systems evaluated including why these MOPs are important to system design and how they are scored. These MOP value scores are then used in the MOE value scores to evaluate overall component scores for system functions.

a. USW Depth Score

The first MOP metric score that will be discussed for the underseas warfare systems is the depth score. The depth that submersible system can operate provides various advantages to the systems over a range of operations. Depth allows acoustic sensing systems to operate at longer ranges and different environmental aspects of the water column can be utilized at different depth for sensing. Increased operational depth also provides offense and defense advantages for the systems as the system can operate more freely in the underwater battlespace. In these ways the ability for an underwater system to operate at depth effective the sensing, denial, and control system function.

Due to this importance of depth in the operation of underwater assets it was determined that the system parameter would be assigned a score. Due to the littoral nature of this system design, it was determined that depth should only be a factor to the depth associated with the littoral areas. Looking at the two scenarios it was determined that value would only be added until the operational depth of 500 m. It was also determined that the value of depth would only be associated with a linear curve. This led to the following expressions for a depth score:

$$For\,systems\,with\,max\,depth\,up\,to\,500m : Depth\,Score = \left(\frac{Max\,Depth\,in\,metres}{500} \right) \times 10$$

$$For\ systems\ with\ max\ depth\ beyond\ 500m : Depth\ Score = 10$$

These two expressions create a depth score that ranges from 0–10 that is linearly based on the max depth that the system can operate.

b. USW Speed Score

The speed that an underwater system can operate within the ocean environment is another aspect of an underwater system that highly affects many aspects of the system's function. The faster the speed that an underwater system can operate within the underwater environment, the better it is able to sense and act within it. Due to these distinct advantages that speed plays for this system it was determined that this would be a MOP that would need to be scored for the underwater system under consideration.

In determining what values for speed scores to associate with possible system speeds, environmental considerations were considered. For a system to be effective in the underwater environment, the operational speed that system would need to be greater than that of the underwater currents that act upon the system. Although these environmental factors differ in different regions in the world, it was determined the generally for an underwater system to be effective worldwide it would need at least a 1.5 kn speed to generally be able to operate against the currents in various parts of the world. It was therefore determined that if a system was only able to operate at a max speed of 1.5 kn or less it would have a value score of 0. It was also determined that from 1.5 to 10 kn the value of the speed scores would linearly increase. Beyond 10 kn it was determined that no additional value would be added to a system. This led to the following equations for speed score:

$$For\ systems\ with\ max\ speed \le 1.5\ knots : Speed\ Score = 0$$

$$For\ systems\ with\ max\ speed\ \ from\ 1.5 - 10\ knots : Speed\ Score = \frac{Max\ Speed\ in\ knots}{10 - 1.5} \times 10$$

$$For\ systems\ with\ max\ speed\ beyond\ 10\ knots : Speed\ Score = 10$$

Overall, this means that the speed score is linear from 0–10 based on the speeds from 1.5 to 10 kn.

c. USW Sensor Score

Sensors are important because these are the ways that the individual units can gain combat information on the underwater environment. Due to the differing development of these various systems, some have a large set of sensors, others have none. Because understanding the sensors capabilities is a complex enterprise in the underwater domain and there are many diverse sensors utilized for the various systems a simple scoring regime on a 0–10 scale was utilized. This scoring regime assigned 0 points if there were no sensors, 5 if simple sensors utilized and 10 if there was a set of underwater sensors utilized for this system. The scoring regime is shown below:

$$For\ systems\ with\ no\ sensors: \quad Sensor\ Score = 0$$

$$For\ systems\ with\ one\ basic\ sensor: \quad Sensor\ Score = 5$$

$$For\ systems\ with\ multiple\ sensors: \quad Sensor\ Score = 10$$

d. USW Weapon Score

Like the sensor score, a simple weapons scoring was utilized for undersea vehicles based on the current ability of the system to integrate weapons. If the system does not currently have weapons systems associated with it would not receive a value score for weapons. If there currently is an integration of the weapons system with the systems, it would receive a score of 10. This leads to the following scoring regime.

$$For\ systems\ with\ no\ weapons: \quad Weapon\ Score = 0$$

$$For\ systems\ with\ weapons: \quad Weapon\ Score = 10$$

e. USW Weight Score

The weight of an underwater system has many overall systems effects to system performance. Depending on the overall system configuration, the weight of the underwater systems may influence the sustainability of the systems as larger heavier systems generally are more maintenance intensive. Additionally, heavier systems will affect the ability of the units to be deployed by other systems such as aircraft. Due to the inverse weight relationship between weight and value for a system, it was determined that a scoring system would be created that would give lower scores for systems that had higher weights. To incorporate the impact of weight on air mobility for these systems a tiered value system was created based on the maxim load weight of the light helicopters like the MH-60 and medium transport aircraft like the C-17 which would be the two possible systems that would be utilized to transport this system. This led to the following scoring systems:

$$For\ weight > 2700\, kg : Weight\ Score = 2$$

$$For\ weight \leq 2700\, kg : Weight\ Score = 5$$

$$For\ weight \leq 100\, kg : Weight\ Score = 10$$

f. *USW Fuel Type Score*

The type of fuel that an underwater system utilizes for electrical generation and propulsion has many effects on the overall system operation and needed to be incorporated into the overall systems value model. The infrastructure that is required to support these systems will differ depending on the type of fuel utilized by the underwater system. During domain group discussions it was determined that battery charging electrical systems utilized by underwater systems would be the least advantageous as it would require an electrical charging infrastructure to be developed to support these systems. Systems that utilize normal marine fuels were determined to have slightly more value as those systems would not require significantly more infrastructure to support their mission. Finally novel systems that did not require a conventional fuel source were determined to be the most advantageous as they would not require additional infrastructure to support the system These “novel” systems include the Slocum Glider’s thermal engine design. To reflect these values associated with different fuel systems, the following fuel type scoring regime was implemented for underwater systems:

$$For\ Electric\ Battery\ Systems : Fuel\ Score = 6$$

$$For\ Electric\ Battery\ with\ Diesel\ Recharge\ Systems : Fuel\ Score = 7$$

$$For\ Novel\ Systems\left(e.g.Thermal\ Engine\right) : Fuel\ Score = 10$$

g. USW Endurance Score

Finally, the endurance of underwater systems was a general aspect of underwater systems design that was taken into consideration for the value systems design. For the overall system design the amount of endurance the individual vehicles have impacts design as more support infrastructure is required for low endurance vehicles to support their refueling/recharging. Additionally, low endurance underwater vehicles will likely require many replacements so that their system functions can be continually accomplished. During the domain group conversations, it was determined that systems that although the maximum endurance is desired for these underwater systems, the ability to operate beyond 6 months would be equally valued as the operational construction of the system was that these operations would not last longer than this time. It was then determined that three other endurance categories would be created for system operating less than 6 months. The overall scoring of these categories base on systems endurance are shown below:

$$For\ systems\ with\ endurance < 72\ hours : Endurance\ Score = \frac{Endrance\ time\ in\ hours}{72 \times 5}$$

$$For\ systems\ with\ endurance\ between\ 72hrs - 2\ months : Endurance\ Score = 6$$

$$For\ systems\ with\ endurance\ between\ 2 - 6\ months : \quad Endurance\ Score = 8$$

$$For\ systems\ with\ endurance > 6\ months : Endurance\ Score = 10$$

2. MOE Value Scoring

In this next Section we will go into how the overall MOE value score was calculated for the underwater systems based on the MOP scores calculated earlier. These MOE value scores are associated with the overall system functions and systems MOEs discussed in the earlier Section about system MOEs. All calculated MOE metrics are standardized on a scale of 0–10 utilizing MOP metrics which used 0–10 scoring systems.

a. USW GMBA Score

For the GMBA system function for the undersea warfare the depth, speed and sensor MOP scores were utilized to calculate this value. Due to the unique nature of the underwater environment, the ability for an underwater system to sense is not only a function of the sensor utilized but also the depth that the systems are operating. Speed is a factor for these score calculations as systems with higher speed are better able to conduct a search of the area and can operate in a better manner to maneuver to make use of their sensors.

Due to the importance of all three of these MOP scores in the GMBA function the following Equation was utilized to calculate the GMBA score for undersea systems.

$$GMBA\,Score = \frac{Depth\,Score + Speed\,Score + Sensor\,Score}{3}$$

This Equation provides an overall score for undersea systems that equally weighs depth, speed, and sensor factors into the overall score for this function.

b. USW Denial Score

For the denial system function of the undersea warfare systems, the depth, speed, and weapon score were utilized to calculate the MOE value score. Unlike the GMBA score, the denial score was heavily connected to a single MOP value score, the weapons score. If the system that was under evaluation scored 0 for the weapons score, as it did not have any weapons, the denial score would be 0 as it would lack the capability to deny the enemy the ability to utilize the underwater environment.

Like the GMBA value score, when the weapons score is above a value of zero the depth and speed scores contribute to the denial score. This is done to consider the advantages that speed, and depth provide in the employment of weapons systems in the underwater domain. This leads to the following Equations for denial MOE value score.

$$\text{If Weapon Score} = 0,\ \text{Denial Score} = 0;$$
$$\text{Else: Denial Score} = \frac{\text{Depth Score} + \text{Speed Score} + \text{Weapon Score}}{3}$$

c. USW Control Score

As in this systems context, control is a function of the survivability of a system in the combat environment, for an underwater system the MOP value scores of depth speed and weight are considered in the calculation of the MOEs. For the control MOE for underwater systems, speed and depth were important facts to consider as these influenced the ability for a system to avoid form being targeted. Weight was another system MOP factor that was considered as during domain discussion it was evaluated that larger systems were determined to be more survivable. To incorporate the previously defined weight score into the control score the inverse of the calculated weight score was utilized for this Equation as this would give higher value for heavier systems. From this evaluation the following Equation was created for the overall control score:

$$\text{Control Score} = \frac{\text{Depth Score} + \text{Speed Score} + (10 - \text{Weight Score})}{3}$$

d. USW Sustain Firepower Score

The final score that was calculated for undersea systems was for the function of the system sustainability. In this score, the MOP scores for weight, fuel time and endurance were utilized. Weight was an important sustainability factor to consider as in general the larger the system, the more burdensome the sustainability requirements for the system would be including logistical and maintenance requirements. Fuel type scores were utilized as that MOP score captured the impact that different fuel types for underwater system impact the required infrastructure for the system which also impacts the sustainability of the system. Endurance scores were also utilized in the calculation of the undersea sustain score as it was determined that system with higher endurance would be more sustainable as a combat system as less supporting infrastructure is required to enable operation of these systems. All three of these MOP value scores were equally weight in the following Equation for sustain scores:

$$Sustain\ Firepower\ Score = \frac{Weight\ Score + Fuel\ Type\ Score + Endurance\ Score}{3}$$

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IX. SYSTEM OPTIMIZATION AND CANDIDATE SYSTEM GENERATION

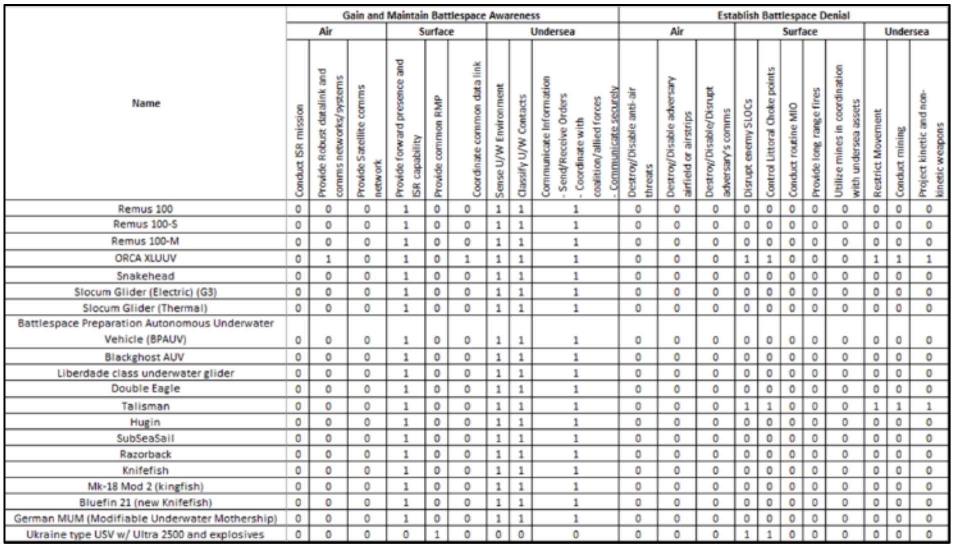
After developing this list of possible domain components for this LDS, the team decided that it was time to begin the process of selecting components from this list to best meet the LDS's requirements. This would be difficult task as we would not only need to seek to maximize value (as calculated in the earlier value design process) and meet all functional requirements but also deal with all the various system constraints (budget) and do this in an impartial process.

To be able to accomplish this selection process several tasks were conducted. First a component-function matrix was created to connect the components that were investigated to sub-functions defined as requirement during the functional decomposition. This component-function matrix was then combined with the value design data, along with other system constraints to develop an optimization program to recommend sets of components solutions. Finally, different inputs were given to this optimization to get candidate systems recommendation for a range of littoral denial missions.

A. COMPONENT-FUNCTION MATRIX

For the overall LDS to be effective, all sub-functions that were derived during the functional decomposition would need to be incorporated in the design. To accomplish this, it was determined that all the component platforms that were evaluated would need to be assessed on their ability to accomplish these various tasks. To properly document the accomplishment of these various component systems for these sub-functions, a component-function matrix was created.

This matrix listed all the various components under consideration for the system in the rows of the matrix. In the columns of the matrix the various sub functions that need to be accomplished are recorded. Within this matrix the ability of the different components to accomplish these functions is recorded. Figure 14 shows a selection of this component-function matrix for the undersea systems assessed, with values of one noting that the component accomplished the sub-function, where zeros indicate the component does not.



Name	Gain and Maintain Battlespace Awareness									Establish Battlespace Denial										
	Air			Surface			Undersea			Air			Surface					Undersea		
	Conduct ISR mission	Provide Robust datalink and comms networks/systems	Provide Satellite comms network	Provide forward presence and ISR capability	Provide common RMP	Coordinate common data link	Sense U/W Environment	Classify U/W Contacts	Communicate Information - Send/Receive Orders - Coordinate with coalition/allied forces - Communicate securely	Destroy/Disable anti-air threats	Destroy/Disable adversary airfield or airstrips	Destroy/Disable/Disrupt adversary's comms	Disrupt enemy SLOCs	Control Littoral Choke points	Conduct routine MIO	Provide long range fires	Utilize mines in coordination with undersea assets	Restrict Movement	Conduct mining	Project kinetic and non-kinetic weapons
Remus 100	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Remus 100-S	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Remus 100-M	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
ORCA XLUUV	0	1	0	1	0	1	1	1	1	0	0	0	1	1	0	0	0	1	1	1
Snakehead	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Slocum Glider (Electric) (G3)	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Slocum Glider (Thermal)	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Battlespace Preparation Autonomous Underwater Vehicle (BPAUV)	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Blackghost AUV	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Liberdade class underwater glider	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Double Eagle	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Talisman	0	0	0	1	0	0	1	1	1	0	0	0	1	1	0	0	0	1	1	1
Hugin	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
SubSeaSail	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Razorback	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Knifefish	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Mk-18 Mod 2 (kingfish)	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Bluefin 21 (new Knifefish)	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
German MUM (Modifiable Underwater Mothership)	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Ukraine type USV w/ Ultra 2500 and explosives	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0

Figure 14. Partial Image of Function-Component Matrix

This component-function matrix was created for all components evaluated and systems functions across domains. One of the major advantages of this large component-function matrix was that it was able to evaluate how systems in one domain were able to accomplish functions across various domains. This came into advantage later when the optimization tool was utilized to evaluate which set of components best met system requirement as optimization was made to across all domains.

B. PLATFORM COMBINATION OPTIMIZATION PROGRAM

The team determined that use of a mathematical optimization program was an appropriate tool to help determine what set of components could be selected to maximize value of the LDS while considering the various constraints to the system. The development of this tool was helpful as it allowed for impartial recommendations to be created based on value scores created earlier as well as dealing with the complexity of component selection process.

To make this optimization program the component value scores were combined with the component-function matrix and various system constraints to create an executable optimization program. In the following Section the aspects of this optimization program will be discussed including the independent variables, parameters and constraints used for this program.

1. Independent Variable

The one class of independent variables for this program is the number of different systems that are utilized in the final design. In this optimization program these different potential systems are noted with a single set of decision variables that include an index number i along with information about what type of domain the system belongs to note with variable j. The basic information about the independent variable for this optimization program is shown below:

$$X_{i,j} = X\ Number\ of\ System\ i\ \ of\ Types\ j\ Selected$$

$$j = Domain\,Type\begin{cases} Air = Air\ Domain \\ Sur = Surface\ Domain \\ USD = Undersea\ Domain \end{cases}$$

2. Parameters

In this optimization program there are several system program parameters that are utilized with the independent variable to create this optimization program. Each of these parameters will be briefly described below.

a. Value of Component System

Through the system value design process, described in the previous Section, these various potential components of the LDS have associated values assigned for each basic function completed by the system. For this optimization program, the values of these system (for each function and domain type) are expressed with the following parameter:

$$V_{i,j,k} = Value\ of\ System\ i\ of\ Type\ j\ of\ Function\ k$$

$$k = Function\,Type \begin{cases} GMBA = GMBA\,Function \\ Deny = Denial\,Function \\ Cont = Control\,Function \\ Sust = Sustain\,Funciton \end{cases}$$

These values would be directly pulled from the calculated values scores made during the value system design process and were directly inputted into the program.

b. Weights for Domain and Function

To make this program more tailorable to the various needs of a global security environment, weights were needed on the values associated with the system components. The two factors that it was desired to have weights associated with value scores were for the domains and functions. This would allow the project team to tailorized the optimization program for different region and mission based on the importance of specific domains and/ or functions. The parameter for weights of these two factors are shown below.

$$Wd_j = Weight\ for\ Domain\ j$$

$$Wf_k = Weight\ for\ Function\,k$$

These two weighting parameters ranged from values of 0–1 based on the leadership’s assessment of each’s importance in the scenario for which the program was run.

c. Maximum Production Parameter

A maximum production parameter was created for this optimization program as it was determined that for different systems as it was determined that within the timeline associated with the created of this LDS, the companies that would create this system would be restricted in the number of systems they could create due to constraints related to production capacity. As these production constraints would vary based on the system being produced, a general parameter was created as shown below:

$$P_{i,j} = Maximum\,Production\,Value\ for\ System\,i\,of\ Domain\ j$$

d. Unit Production Cost

To associate these components of the system with an overall cost, a parameter for unit production costs was utilized in this optimization program. This parameter is the estimated cost of the various systems that were found during the platform review Section of this project, estimates were based on most recent cost data for the system and were associated with current year dollars estimates for the system. The parameter for production unit cost is shown below:

$$C_{i,j} = Unit\ Production\ Cost\ of\ System\ i\ of\ Domain\ j$$

e. Function-Component Parameter

A final parameter was utilized in this optimization program to incorporate the function component pairing as discussed in the previous Section. This is a binary parameter that is associated with whether an associated system component would be able to accomplish a system sub-function. This parameter is shown below:

$$B_{i,j,l} = Does\ System\ i\ of\ Type\ j\ Accomplish\ Subfunction\ l \begin{cases} 1 = Yes \\ 0 = No \end{cases}$$

3. Objective Function

The overall objective of this optimization program is to select individual components so to provide the best value of a LDS subject to all the constraints of this project. This means that the overall objective function for this program is a function of the summation of all different value contributions of the systems utilized in this LDS.

Additionally, in this objective function, weights are utilized to tailorize the optimization program for the differing mission environments in which importance of domains and system functions differ.

This leads to the following optimization function:

$$Maximize \sum_{k}\sum_{j}\sum_{i} Wf_k Wd_j V_{i,j,k} X_{i,j}$$

4. Constraints

In this subsection the various constraints that were utilized for this optimization program. Each of these constraints relate to a specific aspect of the design of the LDS that needed to be incorporated into this optimization program.

a. Decision Variable Integer Constraint

One of the first constraints that was implemented in this optimization program was the integer constraint associated with the decision variable. As no fractional amount of a system could be utilized in this LDS, it was important that this integer constraint be incorporated into this program.

$$X_{i,j} \in \mathbb{Z} \quad \forall\ i\ j$$

b. Sub-function Accomplishment Constraints

Another constraint that needed to be included in this program was one that ensured that all sub-functions that were determined to be required for this system were accomplished. This constraint was done by utilizing the binary function-component parameter with the decision variable. By multiplying these two variables together and summating them over all system and domains an expression was created showing the number of all systems that could accomplish an associated sub-function.

Through leadership group discussions it was determined that a minimum of five systems were needed to accomplish each sub function, to ensure that redundancy was achieved for all sub-functions.

This led to the following expression of sub-function accomplishment constraints for the set of sub-functions (noted by variable l in this expression):

$$\sum_{i}\sum_{j} B_{i,j,l} \times X_{i,j} \geq 5\left(Min\,Value\ for\ Redundacy\right) \quad \forall\, l$$

This set of constraints ensured that all sub functions were able to be accomplished by at least five units in the recommended system.

c. *Maximum Production Constraints*

Due to the known restriction on production of the various systems, this constraint was added to ensure that the optimization program is restricted to only select a number of components for the system that is less than or equal to the maximum production parameters. Below is the expression for the production constraint:

$$X_{i,j} \leq P_{i,j} \quad \forall\ i, j$$

d. *Budget Constraint*

Using the independent variable and the parameter for per unit cost for the various systems, a maximum budget constraint was created. This maximum budget constraint was desired as it allowed for the optimization program to be set up to restrict the selection of the various systems to a simple budget number. This was important for this program as overall systems cost is an important aspect of this design that needs to be considered. Below is the single budget constraint for this optimization program:

$$\sum_{i}\sum_{j} C_{i,j} \times X_{i,j} \leq Max\,Budget$$

e. *Max Domain Specific Components Constraints*

The final constraint that was utilized for this optimization program was a constraint for the maximum number of domain specific components for this system. Due to the nature of the operating environment of this LDS, it was determined that a maxim number of domain specific components could be a constraint for the optimization program. This would prevent the optimization program from selecting an unreasonable number of systems of a specific domain and was an additional tool to help tailorize the optimization tool for different littoral denial missions.

$$\sum_{i} X_{i,j} \leq Max\,numer\,of\,unit\,type, \quad \forall\ j$$

Concluded to say that all these aspects of the program were able to be accomplished in excel with an executable "code."

C. CANDIDATE SYSTEMS RECOMMENDATIONS

The various candidate systems that were generated from the optimization program will be discussed in the following sections. The first section covers general parameters that were utilized for all scenarios in creating possible alternatives. Then, baseline system recommendations are discussed where functions and warfare areas are equally weighted. Following the baseline system, two scenario-specific systems were generated by altering the optimization program's various weighting parameters.

1. Basic Optimization Parameters Description

During the optimization program's candidate system generation, several aspects of the optimization program remained the same. One of these factors was the number of different potential systems under investigation, where the same 58 different potential platforms were utilized as potential decision variables. For these 58 platforms under investigation, specific parameters were assigned in the optimization program based on the platform's advertised or assumed performance metrics. These parameters include the unit cost and functional value scores, as well as binary function-component parameters.

The required system functions used in the optimization program were taken from the functional decompositions as described previously in this report. From the functional decomposition, it was found that of the 58 systems under investigation there were 32 unique sub-functions that the various systems could accomplish, which influenced optimization constraints for the system of systems.

For all systems developed from this optimization tool, a budget constraint was instituted for a total of $1.5 Billion, which was developed from a simplified comparison to the cost of two Arleigh Burke-class destroyers. The team estimated that total acquisition costs for two Arleigh Burke-class destroyers would be over $4 Billion but to make our LDS competitive, it was ideal that total system costs should aim to be less than this cost. Our team therefore estimated that $1.5 would be sufficient for an acquisition constraint as the other $2.5 billion for this LDS could be spent on other aspects of the system such as logistical support, maintenance, and manned operating and monitoring costs. This breakdown of estimated cost for the LDS is shown in Figure 15.

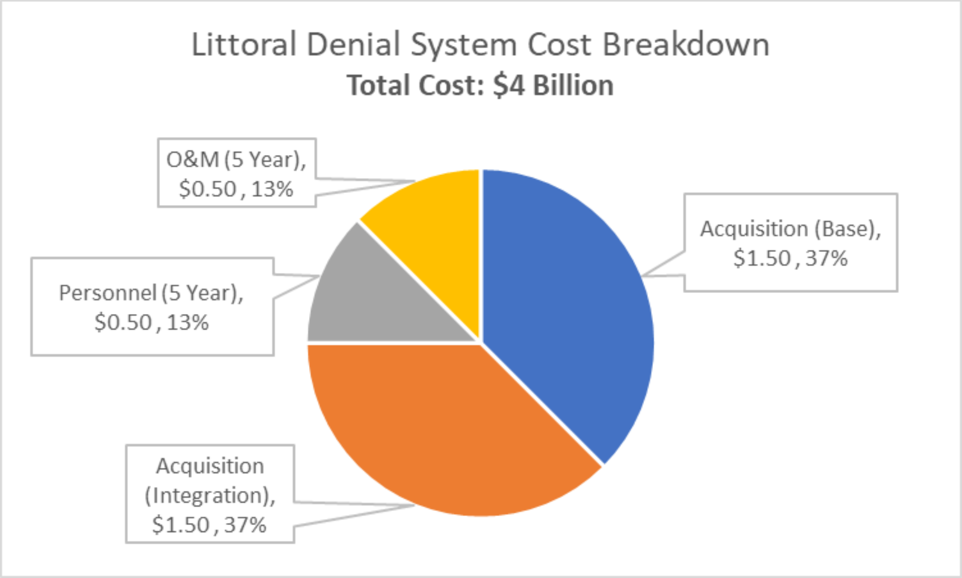


Figure 15. Chart Displaying Cost Breakdown Assumptions of LDS

For all scenarios in which that optimization program was utilized, production constraints were set for 500 units, corresponding to a general estimation of production capacity that various unmanned systems manufacturers would have over a five-year acquisition period. This general estimation on production capacity constraints could be later improved by more specific production estimates for various systems.

Due to the size of the physical space that this system would operate, it was determined that a constraint should be implemented to restrict the number of systems of certain domains that the optimization tool recommends. This was done to prevent the optimization tool from selecting an unrealistic number of systems for one domain. Due to the high-cost nature of unmanned air systems paired with a goal of utilizing attritable COTS products, it was determined that a constraint for a maximum of 250 air units would be implemented in the optimization tool. For undersea and surface units, this maximum constraint was set at 500. The following sections detail the various systems that were generated from the optimization program, along with different weighting decisions made to account for mission scenarios.

2. Baseline System

As our system design is ideally intended for *global* littoral use, the team envisioned a foundational system that served as a "one size fits all" system, where external factors did not influence platform combination selection. This would also allow for the same optimization tool to be used when tailoring unmanned platform selection for a specific scenario, its environment, and adversary of concern. To establish this default system, the weighting for each function was set to 1.0, such that no system function had priority of importance or influence over another. Similarly, without a designated adversary to influence the tool, each domain weighting influence was also set to 1.0, balancing domain platform selection priority. Table 8 shows the baseline system as produced from the optimization tool described in previous sections.

Table 8. List of Platforms for Baseline LDS

UAV Platforms	USV Platforms	UUV Platforms
(5) XQ-58A Valkyrie	(5) LMACC	(40) Slocum Glider
(5) MQ-25 Stingray		(40) Talisman M
(175) V-Bat 128		(400) Hugin 3000
65 Skyway		(500) Mk-68 Mines

3. Gotland Modified System

Using the same optimization tool and system constraints as the baseline LDS, the team altered the domain weighting to fit the Gotland scenario. Considering the Russian Baltic fleet and the assessed strengths and weaknesses of their platforms, along with environmental and bathymetry concerns, the team prioritized the undersea domain in the optimization tool by doubling the weight of these potential platforms (from 1.0 to 2.0). All other domain platform weights remained at 1.0, along with all functional weights. The Gotland-tailored LDS platforms are listed in Table 9.

Table 9. List of Platforms for Modified LDS (Gotland)

UAV Platforms	Surface Platforms	UUV Platforms
(170) V-Bat 128	(5) LMACC w/ LRASM, SLQ-32, SPS-73, and Ultra 2500	(500) Talisman
(121) Skyways v2.6b		(40) Slocum Glider G3
(5) MQ-25 Stingray		(416) Hugin
(40) XQ-58A Valkyrie		(1) Bluefin 21
		(495) Mk-68 Mine

With an emphasis on undersea platforms, the optimization tool prioritized UUV platforms with longer undersea sensing ranges and endurance capabilities such as the Slocum Glider, as well as undersea denial assets that can deny undersea and surface domains such as the Mk-68 mine. Although optimization results for the Gotland scenario reflect the team's decision to stress undersea domain, the ultimate appropriateness will be assessed during modeling and simulation efforts.

4. Palawan Modified System

Similar to the Gotland LDS, the team used the same optimization tool and system constraints as the baseline LDS but altered the weighting for the Denial function to fit the Palawan scenario. Considering the large quantitative advantage possessed by PRC assets, associated platform strengths and weaknesses, and environmental and bathymetry concerns, the team prioritized the Denial function in the optimization tool by doubling its weight (from 1.0 to 2.0), emphasizing the need to maximize RED attrition. All domain platform weights remained at 1.0, along with remaining functional weights. The Palawan-tailored LDS platforms are listed in Table 10.

Table 10. List of Platforms for Modified LDS (Palawan)

UAV Platforms	Surface Platforms	UUV Platforms
(40) Kratos XQ-58A Valkyrie	(495) Semi-submersible USVs equipped with Ultra 2500 and Explosives	(500) Talisman
(121) Skyways v2.6b		
(5) MQ-25 Stingray		

With an emphasis on area denial, the optimization tool prioritized platforms with the capability to cost-effectively address the surface platform threat of the PRC, seen in the selection of 495 semi-submersibles. Although optimization results for the Palawan scenario reflect the team's decision to stress Denial-capable assets, the ultimate appropriateness will be assessed during modeling and simulation efforts.

X. COMBAT MODELING

In this section, the combat model that was utilized to test the designed LDS is discussed. First in this section of the overall objective behind creating this combat model is discussed followed by the overall model construct. Next theoretical underpinnings of two aspects of this model, Detention and Engagement, are briefly discussed. Next the specific modeling construct for this combat model is discussed, concluding with discussion on which tools were utilized to build and simulate this combat model.

A. OVERALL OBJECTIVE OF MODEL

Following the development of candidate systems with the optimization program, while continuing to use of the Systems Engineering V process as a guideline, the team proceeded to "move up the V" and validate requirements that were stated at the beginning of the project. To accomplish the verification and validation process, our team began to model the proposed solutions, validating overall system functions. Specifically, it was determined that a simulation program model would validate the system functions of GMBA, deny, control, and sustain firepower. The scenario-specific LDS would also be compared to traditional assets available for this mission, resulting from independent simulations of combat modeling.

Combat modeling was determined to be the best way of validating the four system functions as each of these functions, shared by the various unmanned units in each scenario's LDS, could be appropriately tested in a combat scenario against enemy forces. It was also advantageous as it allowed for complex interactions between large numbers of units to be simulated, while still providing overall system metrics. A combat model was therefore developed to support simulation of both scenarios, comparing the new LDS against units that would have previously accomplished this mission. This simulation attempted to be as realistic as possible, considering the largest number of parameters possible and accounting for project constraints. Additional simulation constraints include computing resources, depth of available platform performance data, time, and simulation capabilities possessed by the team.

B. OVERALL MODEL CONSTRUCT

As a general combat model, the main framework design was to mimic the "kill chain," also known as the detect to engage sequence. Simplified, the mission scenario can be thought of a battle where allied military units face an adversary and attempt to complete this kill chain, while the enemy units simultaneously pursue the same on allied units. Figure 16 shows basic steps for a generalized kill chain, where assets with sensing capabilities search an area for a target. Once a target it detected using organic data, it can be tracked, where its position and motion can be refined. Finally, with proper authorities, the target is engaged.

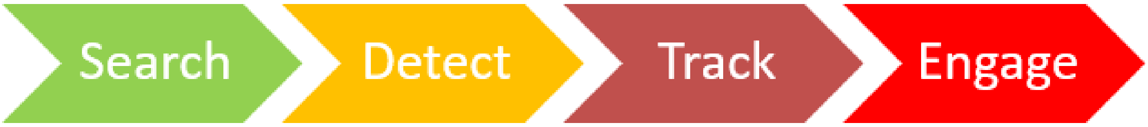


Figure 16. Generic Kill Chain

One particular challenge in simulating a combat model for the given context scenarios is that the variety of platforms present creates a cross-domain problem, where most platforms will have limitations on engageable platforms. For example, undersea assets may be able to detect and engage other undersea platforms and surface assets, but will have limited detection capabilities against air threats, which they will also be unable to engage. Similarly, due to the nature of unmanned assets and current technologies, many unmanned platforms will only have the capability to detect, relying on communication to other assets for engagement, assuming those assets are within striking range. Another difficulty presented in the scenarios is the variety of units, each with unique capabilities and parameters. Due to this variety, paired with the team's limited modeling and simulation experience, some platform capabilities were generalized or assumed in efforts to simplify modeling complications.

The project's combat simulation primarily consists of separate determination of detection and engagement. The following sections discuss the intellectual underpinning of both.

C. DETECTION (SEARCH THEORY)

The first theoretical aspect of the combat model that was addressed is the detection aspect of the generalized detect to engage process. To enable the GMBA and denial functions for the LDS, it was critical that the combat model sufficiently simulate the detection capabilities of the various platforms, to include platform speed. In addition, the detection aspect of this combat model must properly reflect that each platform's sensing capabilities depend on the type of sensor used, environmental considerations, and stealth capabilities of enemy units. Additional challenges include detection across three different warfare domains.

Because of the inherent complexities of attempting to model many different types of units with different detection properties, a simple detection equation, the "Random Search Equation" as defined in the textbook Naval Operational Analysis (Wagner et al. 174) was utilized as a basis for our combat model and is shown below.

$$P_D = 1 - e^{-\frac{wvt}{A}}$$

In this equation, the probability of detection P_D is a function of the speed of the detecting unit (v), time in which the unit is detecting (t), sweep width of the detecting unit (w) and size of the area (A) in which the detecting unit is searching for a target. This equation has important assumptions including that the searching unit is conducting a "random" search and that the unit that is targeted in the search is uniformly distributed over the area. Another major (optimistic) assumption of this detection equation is that when a sensor has a target within the detecting sweep width, the sensor has 100% detection capability.

For the purposes of this combat model, these assumptions can be accepted as this model was created to evaluate the general detection capability of systems utilized for these purposes, not to evaluate specific detection methods. This relatively simple equation for random search probability was also advantageous as it was flexible enough to be used to incorporated in the combat model, allowing the team to simulate the detection function of hundreds of allied and enemy units across all domains. To effectively evaluate the detection capabilities of the various units, each with differing sensors, several methods were utilized to combine the various induvial detection probabilities into a general detection probability. The detection probabilities, calculated from the various system parameters, are further discussed in the following sections.

D. ENGAGEMENT

After detection has been accomplished by a unit in this combat model, an engagement would be conducted to destroy the enemy unit. This engagement will consist of the tracking and targeting of the unit after detection, as well as allocation of weapons to destroy the target. Once again, due to the complexity of this scenario where there are hundreds of units engaging each other across different domains, some simplifying assumptions were made for this engagement process. In general, we simplified this complex engagement process into a simple probability of kill (P_k) value, whose value would change depending on which unit was being targeted by which, and the characteristics of the target.

Beyond the simple probability of kill values, this combat model will need to incorporate the resource aspects of the engagement function. For most engagements with kinetic means, weapons must be utilized which means that the number of weapons carried by each sensing platform must be accounted for in the model. Additionally, as many of the unmanned platforms that will be utilized in the LDS lack weapons to engage enemy units, the combat model must account for sensor platforms sending detection information to platforms that can engage with weapons. To account for the resources utilized in this engagement process, the combat model needed to include a robust data structure, accounting for the units and their associated weapons. To relay sensing information to engagement-capable units, basic rules needed to be incorporated into the combat model to mirror how units would interact in the designed system.

E. MODELING SYSTEMS PARAMETERS

Specific platform parameters were evaluated to compare expected performance and capability of RED and BLUE forces, which would serve as inputs to the combat simulation model. The metrics employed in this analysis include number of platform units, platform velocity, sensor range, number of weapons, and associated weapon kill probability.

1. Number of Units

The number of units refers to the specific number of each platform considered for both BLUE and RED forces in each scenario. The platforms considered for both allied and enemy forces were modified from existing NWSI scenarios, projecting a realistic order of battle in 10 years. For the case of traditional littoral denial forces, two DDGs were added to the blue order of battle. In the case of the generated LDS, the type and number of units added to the blue forces were the result of the optimization model's recommendation.

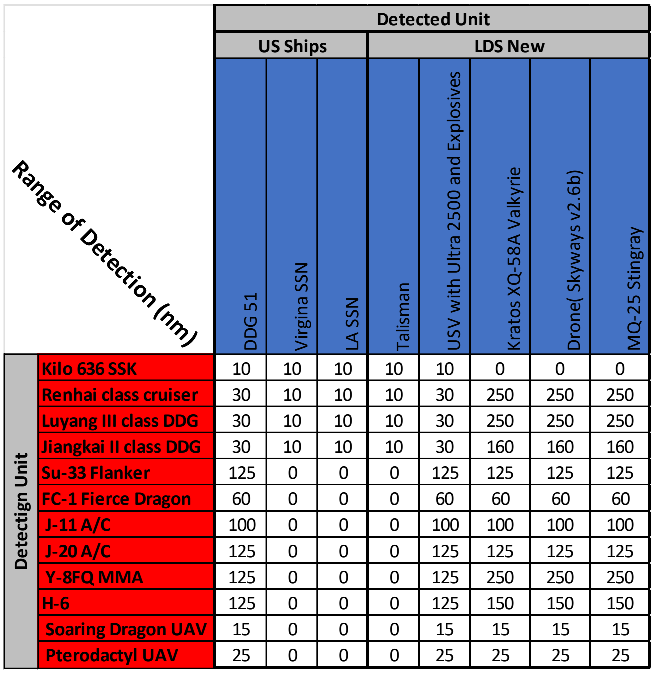
2. Speed

The speed parameter plays an important role for the engagement of the different platforms. It not only has the potential to complement range and weapon utilization capabilities, but also influences the likelihood of survival when attempting to evade enemy weapons. The speed data refers to the operating ("cruising") speed commonly used by the considered platforms, rather than using maximum speed which would have energy or fuel usage implications. The values utilized were determined through research of the standard operating parameters for each platform.

3. Sensor Range

Regarding the sensor range parameter, two different types of information were considered. The first is the maximum detection range for each platform's most capable sensor, relative to possible enemy platforms. The second, as shown in Figure 17, is a specification of the average contact detection range, since the detection distance of each platform will depend on several circumstances such as the platform type and size, its radar and acoustic signature, as well as environmental considerations. Although it is known that environmental conditions have an impact on detection distances, particularly in the underwater domain, certain simplifying assumptions had to be made to enable a mathematical model to determine the first detection.

Similar to platform speeds, the maximum detection distances for each platform were obtained through research conducted in publicly available forums. Additionally, for the individualized detection chart, extensive discussions were held with team members to ensure the simulated detection distances were logical, taking into consideration the factors that were previously discussed.



	Range of Detection (nm)	Detected Unit							
		US Ships			LDS New				
		DDG 51	Virgina SSN	LA SSN	Talisman	USV with Ultra 2500 and Explosives	Kratos XQ-58A Valkyrie	Drone(Skyways v2.6b)	MQ-25 Stingray
Detectign Unit	Kilo 636 SSK	10	10	10	10	10	0	0	0
	Renhai class cruiser	30	10	10	10	30	250	250	250
	Luyang III class DDG	30	10	10	10	30	250	250	250
	Jiangkai II class DDG	30	10	10	10	30	160	160	160
	Su-33 Flanker	125	0	0	0	125	125	125	125
	FC-1 Fierce Dragon	60	0	0	0	60	60	60	60
	J-11 A/C	100	0	0	0	100	100	100	100
	J-20 A/C	125	0	0	0	125	125	125	125
	Y-8FQ MMA	125	0	0	0	125	250	250	250
	H-6	125	0	0	0	125	150	150	150
	Soaring Dragon UAV	15	0	0	0	15	15	15	15
	Pterodactyl UAV	25	0	0	0	25	25	25	25

Figure 17. Example of Detection Matrix Used for Combat Model

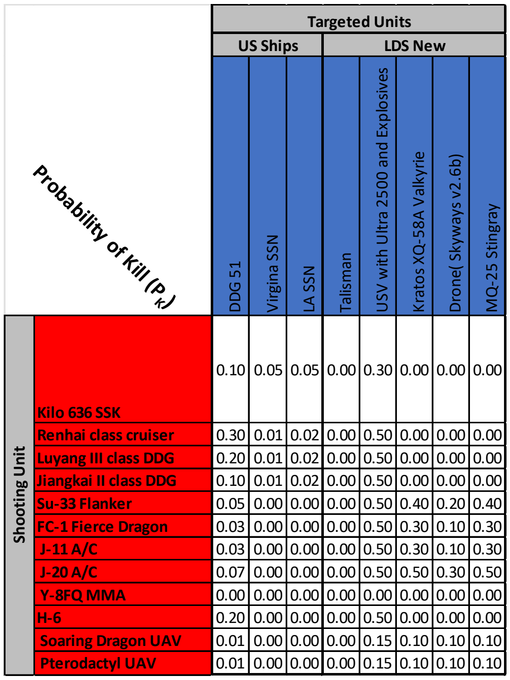
4. Number of Weapons

The attrition model heavily relies on the quantity of weapons, which holds significant importance. Since the proposed model does not incorporate predictions for weapon resupply during the simulation, this information is essentially counted to calculate when combat will cease based on weapon utilization. The input data for the model were assigned with the quantity of weapons that each analyzed platform can carry, based on payload information obtained from open-source publications.

5. Probability of Kill

The attrition model proposed in this project relied on an additional essential dataset: the kill probability for encounters between two specific platforms. Similar to the detection distance data, the attrition model's input data incorporated individual kill probability values. Each platform from the BLUE and RED forces was compared to the opposing team's available platforms. Figure 18 illustrates how these data were processed and organized.

The assigned numbers were the outcome of an internal discussion within the project team. Drawing on principles from the Combat Survivability, Reliability, and Systems Safety Engineering (ME4751) classes, the team considered various factors involved in rendering a system inoperative, such as weapon activation, target detection, successful weapon launch, interception, and destruction upon impact (Adams 2023). As a result, the chosen values remained within the realm of practical feasibility and can be altered using classified information for a more realistic and reliable simulation.



Probability of Kill (P_K)		Targeted Units							
		US Ships			LDS New				
		DDG 51	Virgina SSN	LA SSN	Talisman	USV with Ultra 2500 and Explosives	Kratos XQ-58A Valkyrie	Drone(Skyways v2.6b)	MQ-25 Stingray
Shooting Unit	Kilo 636 SSK	0.10	0.05	0.05	0.00	0.30	0.00	0.00	0.00
	Renhai class cruiser	0.30	0.01	0.02	0.00	0.50	0.00	0.00	0.00
	Luyang III class DDG	0.20	0.01	0.02	0.00	0.50	0.00	0.00	0.00
	Jiangkai II class DDG	0.10	0.01	0.02	0.00	0.50	0.00	0.00	0.00
	Su-33 Flanker	0.05	0.00	0.00	0.00	0.50	0.40	0.20	0.40
	FC-1 Fierce Dragon	0.03	0.00	0.00	0.00	0.50	0.30	0.10	0.30
	J-11 A/C	0.03	0.00	0.00	0.00	0.50	0.30	0.10	0.30
	J-20 A/C	0.07	0.00	0.00	0.00	0.50	0.50	0.30	0.50
	Y-8FQ MMA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	H-6	0.20	0.00	0.00	0.00	0.50	0.00	0.00	0.00
	Soaring Dragon UAV	0.01	0.00	0.00	0.00	0.15	0.10	0.10	0.10
	Pterodactyl UAV	0.01	0.00	0.00	0.00	0.15	0.10	0.10	0.10

Figure 18. Example of Probability of Kill Matrix Used for Combat Model

F. SPECIFIC MODEL CONSTRUCT

With the overall combat model requirements described, basic theorical foundations established for the model, and parameters of the model established, a specific construct for the combat model was established. The goal of creating this model construct was to develop it into an executable discrete event simulation that could be utilized in simulation software. After exploring several different model constructs, the simulation and modeling team developed a simple, yet robust and scalable combat model that could be utilized for validation of LDS candidates. Figure 19 shows the basic combat model framework. The simplified diagram shows a flow chart of how the combat model replicates the detection and engagement functions. As shown, RED and BLUE forces are modeled with each side having three different types of units. The engagement process is conducted from left to right of the diagram starting at the source block and ending at either the unit killed or unit survived block. For readability, most of the arcs after the targeted unit set of block have been removed, but the same principles remain.

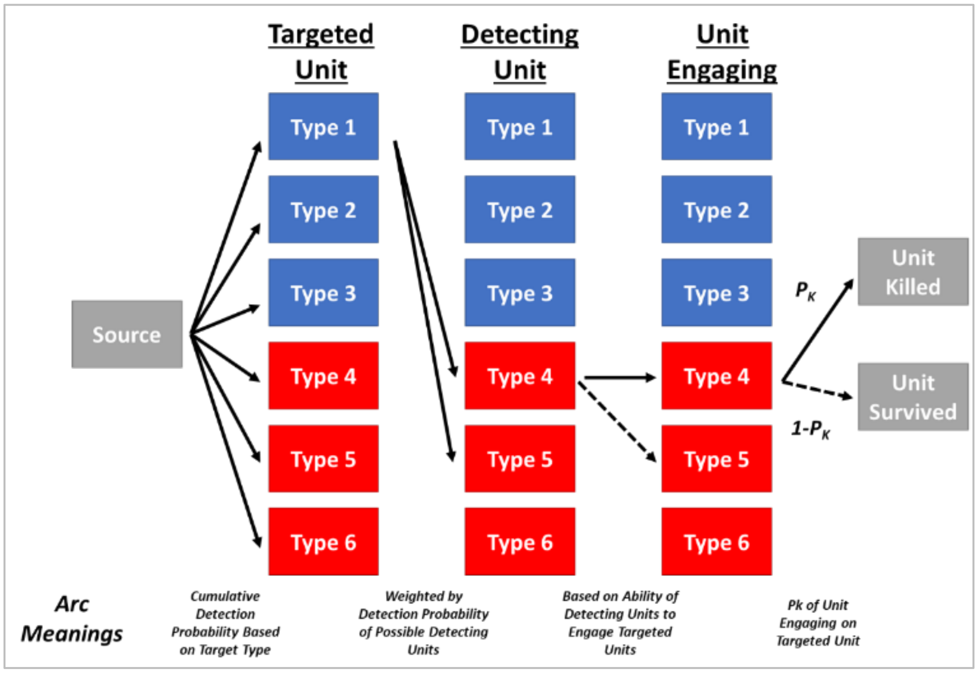


Figure 19. Basic Framework for LDS Combat Model

The following details the overall process of the combat model used. At the source block, an initial discrete event occurs, representing a detection of an opposing unit. This process is represented by the different arcs from the source block to the various targeted units. The weight of each of these arcs are associated with the cumulative detection probability of that unit, based on the number of units that can detect that type of unit as well as their detection parameters, defined in the random search equation (sensor speed and sensor range). As these parameters will be continuously updated throughout the combat model, these arcs weights will change as units are destroyed. In a discrete event simulation, this combat model can then be utilized to first determine what unit was detected by each event. At this point in the model, the event can associate the various aspects of the detected or targeted unit to the event for the next steps in the model.

In the next step of this model, the detected unit is assigned for the targeted unit. This order of block may seem counterintuitive, however due to the fact the random search equation is utilized in the first set of arcs mitigates this. That the detecting unit is assigned after the unit found is not a concern, as all factors of the detecting units have been accounted for in the initial arcs. The arcs from the targeted units to detecting units are weighted in a similar manner to the previous arcs, with weights being associated with the detection probability of the various units. However, in this case, the arcs are from the targeted units to the units that could have detected that target. In Figure 19 for example, the BLUE "Type 1" unit was detected and the only two types of units that could detect this "Type 1" were the RED unit "Type 4" and "Type 5." In this case, weight of these arcs would specifically depend on the BLUE "Type 1" detection probability of the two types of RED forces. Although the directions of these arcs differ depending on which units can detect each other, these arcs will always point from BLUE units to RED or vice versa.

After a detecting unit is assigned for the targeted unit, an engaging unit will be assigned. In general, the detecting unit is also the preferred engaging unit for this combat model. However, if the detecting unit is unable to engage the targeted unit, possibility because the detecting unit has expended its weapons or because it lacks the engagement ability, it will pass the engagement to a unit that is able to engage the targeted unit. The number of arcs and the logic of they pass from detecting units to engaging units will be specific to each set of units used in the combat model. If no systems can engage on the targeted unit, the event terminates, and another begins at the source block. In the example shown in Figure 19, the RED "Type 4" unit that detected the BLUE "Type 1" unit will engage it if is able but will pass the engagement to the RED "Type 5" unit if unable.

If the targeted unit is engaged, the event moves to the final set of arcs. This final set of arcs is weight based on the probability of kill of the various weapons systems utilized on the targeted unit. From each of these blocks, two arcs will be present, where one is associated with the probability of kill of the weapon system on the targeted unit and the other is the probability of survival, which is the complement of this probability of kill. Each of these arcs will terminate the event in the unit killed or unit survived box, which will affect the overall combat model accordingly.

If the event reaches the unit killed box, then the overall number of the targeted units in the model is reduced by one unit. The unit that engaged the targeted unit will also have the number of weapons reduced by one weapon. Again, following the example from the Figure 19, if the arc is taken that leads to the "Unit Killed" block, the number of "Type 1" units is decreased by one as well as the number of weapons associated with the RED "Type 4" units. In the case that the event ends at the "Unit Survived" block, the number of weapons of the engaging unit is still decreased by one but the number of target units does not reduce. Of note, during implementation of this process, alterations were made to account for the special case of mines, which served as units which are destroyed after engaging a target.

What was described previously was the process for one event in the combat model. In the implemented combat model, these events continuously occur until a model stopping condition was reached. One of these stopping conditions for this model was the elimination of units on one side through this detection and engagement process. Another stopping condition was if all weapons on either side were completely expended. A final stopping condition for this combat model would be if there was what the team described as a "Sensor-Shooter Mismatch," it was situations in which neither side had their units eliminated or were completely out of weapons but due to the situation remaining units could only sense certain units do not engage them with the weapons available. In case where these “Sensor-Shooter Mismatch” occurs, the combat model would need to terminate to prevent endless repetition of the detection-engagement process.

This combat model revealed functional performance metrics for the GMBA, denial, control and sustain firepower metrics. Through this model, the basic metrics of the LDS and opposing forces for each scenario could be inputted to a simulation run, yielding simplified results in the forms of attrition for both sides as well as weapons expenditures. Thus, the simulation model provided a means to validate that our developed system designs were appropriate for the requirements we set out to accomplish.

G. BUILDING THE MODEL

During the course of the model construction, two different programs were considered. Simio was considered first, as the modeling team had more collective experience with the program. However, the model proved insufficient for the modeling needs of the team and the decision was made to utilize R instead.

1. Simio

Simio is a modeling software designed to simulate queuing or similar flow of objects through entities. (Pedgen, 1). Simio was initially chosen as the diagrams of the basic system conception were familiar to the various Simio users on the simuation and modeling team. An approximation of the system was created in Simio for testing, as seen in Figure 20.

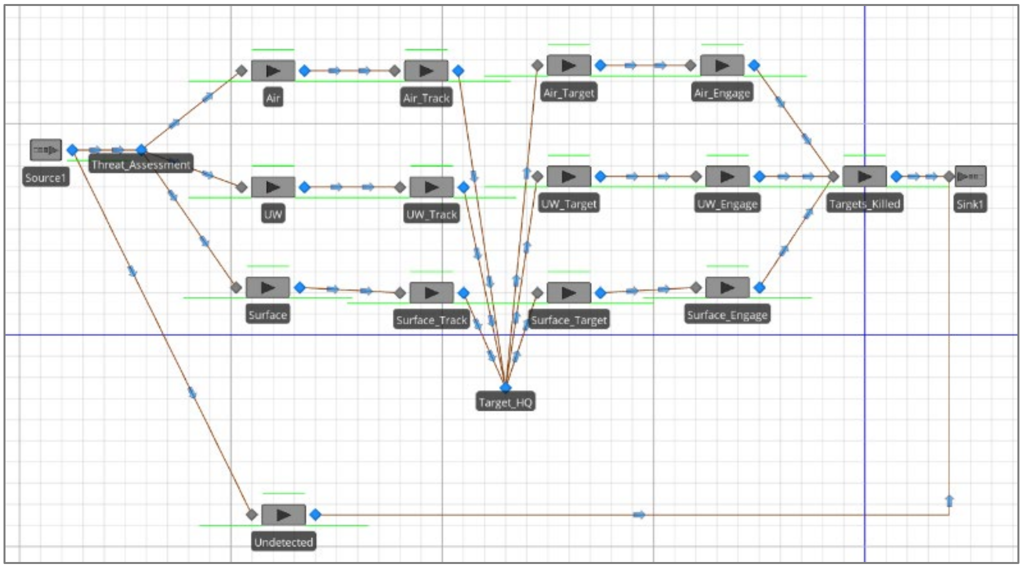


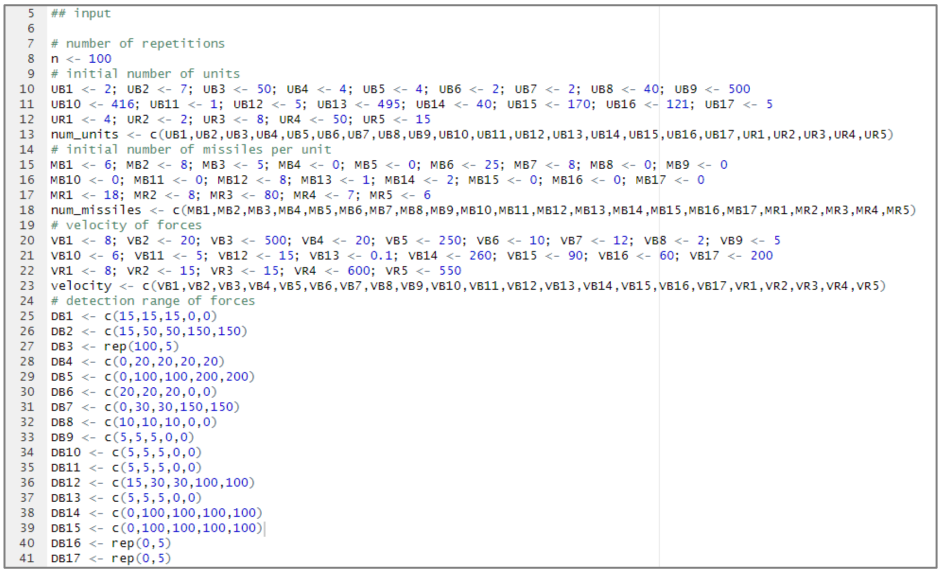
Figure 20. Screenshot of Simio Initial Model

Through testing, the team discovered a number of factors that prevented Simio from being the primary model moving forward. First, the overall lack of experience of the team with modeling at the proposed scale in Simio prevented meaningful progress being made. Additionally, the team was unable to determine a way to allow Simio to model multiple engagements within the various domains to test how the system would perform as a whole. The team would have been forced to model the system's performance by domain rather than as an organic whole. The team assessed that these assumptions would have provided an inaccurate view of how the system behaved and thus was considered an unreliable assumption to make in modern combat. As a result, the team adapted to a more familiar modeling language in R.

2. R

The computer program that the combat model was eventually chosen to model and simulate this combat model was the R programming language. R is an open-source computing "language and environment for statistical computing and graphics" that "provides a wide verity of statistical … and graphical techniques and is highly extendable" (R Foundation 2023). For the purposes of this project, this programming language was very suitable as we found it provides the flexibility needed to create a combat model that had the appropriate functionality, accounting for all aspects of the model that was needed to get the realistic and appropriate results to validate our designed LDS. This flexibility of R as a programming language provided a high functionality but was a more difficult form for our needs in the combat model, especially as we attempted modifications to create run stopping conditions and have specific logic associated to the engagement.

One of the major advantages for our modeling team utilizing R was the use of R's data structure of arrays and matrices. Due to the large number of units that were utilized in these various scenarios, accounting for these parameters within the combat model was seen to be a great modeling challenge. Through R's data structure that utilized arrays and matrixes, this problem was addressed through developing a robust code, where it was possible to make a model where the basic modeling system parameters were inputted as initial variables with matrixes of initial units being automatically created from this information. An example of this assigning of modeling system parameters in the R code is shown in Figure 21 for the New Modified (Gotland) LDS.

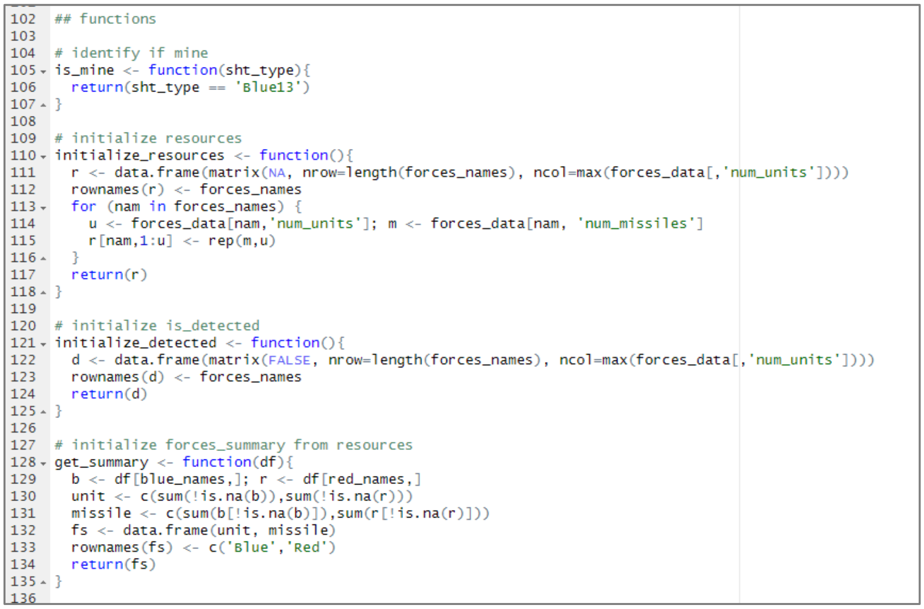


```
## input

# number of repetitions
n <- 100
# initial number of units
UB1 <- 2; UB2 <- 7; UB3 <- 50; UB4 <- 4; UB5 <- 4; UB6 <- 2; UB7 <- 2; UB8 <- 40; UB9 <- 500
UB10 <- 416; UB11 <- 1; UB12 <- 5; UB13 <- 495; UB14 <- 40; UB15 <- 170; UB16 <- 121; UB17 <- 5
UR1 <- 4; UR2 <- 2; UR3 <- 8; UR4 <- 50; UR5 <- 15
num_units <- c(UB1,UB2,UB3,UB4,UB5,UB6,UB7,UB8,UB9,UB10,UB11,UB12,UB13,UB14,UB15,UB16,UB17,UR1,UR2,UR3,UR4,UR5)
# initial number of missiles per unit
MB1 <- 6; MB2 <- 8; MB3 <- 5; MB4 <- 0; MB5 <- 0; MB6 <- 25; MB7 <- 8; MB8 <- 0; MB9 <- 0
MB10 <- 0; MB11 <- 0; MB12 <- 8; MB13 <- 1; MB14 <- 2; MB15 <- 0; MB16 <- 0; MB17 <- 0
MR1 <- 18; MR2 <- 8; MR3 <- 80; MR4 <- 7; MR5 <- 6
num_missiles <- c(MB1,MB2,MB3,MB4,MB5,MB6,MB7,MB8,MB9,MB10,MB11,MB12,MB13,MB14,MB15,MB16,MB17,MR1,MR2,MR3,MR4,MR5)
# velocity of forces
VB1 <- 8; VB2 <- 20; VB3 <- 500; VB4 <- 20; VB5 <- 250; VB6 <- 10; VB7 <- 12; VB8 <- 2; VB9 <- 5
VB10 <- 6; VB11 <- 5; VB12 <- 15; VB13 <- 0.1; VB14 <- 260; VB15 <- 90; VB16 <- 60; VB17 <- 200
VR1 <- 8; VR2 <- 15; VR3 <- 15; VR4 <- 600; VR5 <- 550
velocity <- c(VB1,VB2,VB3,VB4,VB5,VB6,VB7,VB8,VB9,VB10,VB11,VB12,VB13,VB14,VB15,VB16,VB17,VR1,VR2,VR3,VR4,VR5)
# detection range of forces
DB1 <- c(15,15,15,0,0)
DB2 <- c(15,50,50,150,150)
DB3 <- rep(100,5)
DB4 <- c(0,20,20,20,20)
DB5 <- c(0,100,100,200,200)
DB6 <- c(20,20,20,0,0)
DB7 <- c(0,30,30,150,150)
DB8 <- c(10,10,10,0,0)
DB9 <- c(5,5,5,0,0)
DB10 <- c(5,5,5,0,0)
DB11 <- c(5,5,5,0,0)
DB12 <- c(15,30,30,100,100)
DB13 <- c(5,5,5,0,0)
DB14 <- c(0,100,100,100,100)
DB15 <- c(0,100,100,100,100)
DB16 <- rep(0,5)
DB17 <- rep(0,5)
```

Figure 21. Screenshot of R Code of Initial Assigning of Variables

In the R code depicted in Figure 21, all initial modeling system parameters were manually input into the code. This includes the number of units, sensor ranges, velocity of forces, number of weapons, and probability of kill for those weapons for both RED and BLUE forces. For unit parameters that are a function of the opposing units that are being detected or engaged (such as detection range or probability of kill), arrays were utilized. These arrays listed the specific parameters for a single unit across a range of opposing units. Each element of the array is associated with that parameter for a specific opposing unit, as delineated in list of opposing units. For example, in Figure 21, the array assigned at line 25 "DB1" is the detection range of this BLUE unit which is either 15 or 0 NM depending on the RED unit it is sensing.

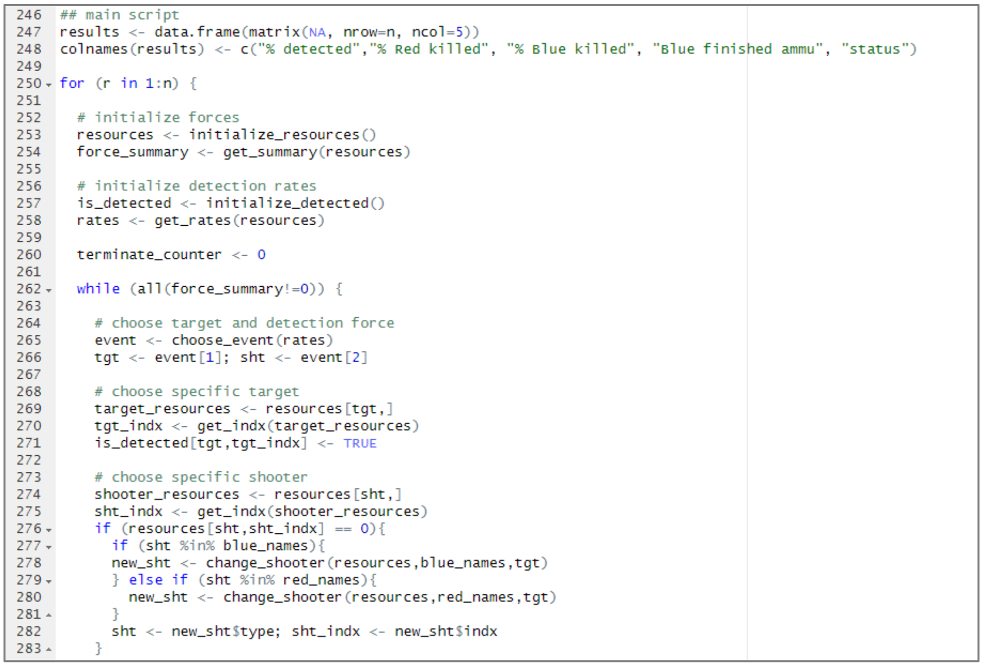
After defining the basic variables for this combat model from the modeling system parameters, several functions were built into the combat model code. These functions conduct various tasks including initializing matrices of units and weapons used in the combat model, selection of detecting units based on the random search equation, conducting basic engagement logic, and updating system measure of effectiveness results. In Figure 22, a small number of the functions utilized in the code for this combat model simulation is shown.



```r
## functions

# identify if mine
is_mine <- function(sht_type){
  return(sht_type == 'Blue13')
}

# initialize resources
initialize_resources <- function(){
  r <- data.frame(matrix(NA, nrow=length(forces_names), ncol=max(forces_data[,'num_units'])))
  rownames(r) <- forces_names
  for (nam in forces_names) {
    u <- forces_data[nam,'num_units']; m <- forces_data[nam, 'num_missiles']
    r[nam,1:u] <- rep(m,u)
  }
  return(r)
}

# initialize is_detected
initialize_detected <- function(){
  d <- data.frame(matrix(FALSE, nrow=length(forces_names), ncol=max(forces_data[,'num_units'])))
  rownames(d) <- forces_names
  return(d)
}

# initialize forces_summary from resources
get_summary <- function(df){
  b <- df[blue_names,]; r <- df[red_names,]
  unit <- c(sum(!is.na(b)),sum(!is.na(r)))
  missile <- c(sum(b[!is.na(b)]),sum(r[!is.na(r)]))
  fs <- data.frame(unit, missile)
  rownames(fs) <- c('Blue','Red')
  return(fs)
}

```

Figure 22. Screenshot of R Code of Selection of Functions

To keep this section of this report at a reasonable length, the all the associated functions utilized in this combat model and how they work will not be covered. It is important to note however that these functions conduct various tasks that allow the combat model to function as described in the "SPECIFIC MODEL CONSTRUCT" section of the report. These functions also were important to the overall development of combat model as these functions allowed the main script to become relativity simplified and for the overall code to be more robust so that new variables could be inputted without having to conduct detailed programming by change the main script code, which is the final aspect of this combat model discussed in this report. Figure 23 shows a screenshot of the first section of this main script used for this combat model.



```r
## main script
results <- data.frame(matrix(NA, nrow=n, ncol=5))
colnames(results) <- c("% detected","% Red killed", "% Blue killed", "Blue finished ammu", "status")

for (r in 1:n) {

  # initialize forces
  resources <- initialize_resources()
  force_summary <- get_summary(resources)

  # initialize detection rates
  is_detected <- initialize_detected()
  rates <- get_rates(resources)

  terminate_counter <- 0

  while (all(force_summary!=0)) {

    # choose target and detection force
    event <- choose_event(rates)
    tgt <- event[1]; sht <- event[2]

    # choose specific target
    target_resources <- resources[tgt,]
    tgt_indx <- get_indx(target_resources)
    is_detected[tgt,tgt_indx] <- TRUE

    # choose specific shooter
    shooter_resources <- resources[sht,]
    sht_indx <- get_indx(shooter_resources)
    if (resources[sht,sht_indx] == 0){
      if (sht %in% blue_names){
      new_sht <- change_shooter(resources,blue_names,tgt)
      } else if (sht %in% red_names){
        new_sht <- change_shooter(resources,red_names,tgt)
      }
      sht <- new_sht$type; sht_indx <- new_sht$indx
    }
```

Figure 23. Screenshot of R Code of Main Script

Overall, this main script contains several programming loops, one of these looks the number of simulations that would be carried out and another nested loop associated with the stopping conditions of the combat model as described in the "SPECIFIC MODEL CONSTRUCT" section of this report. Within these loops, the various functions are utilized so that the discrete events can be simulated following the combat "Basic Framework for

LDS Combat Model” shown in Figure 19. Through this R code, a robust combat model for the LDS was created that was able to simulate the functionality of the different developed systems and evaluate their effectiveness at meeting the overall systems functional requirements.

XI. MODELING RESULTS

The following section presents the outcomes of the combat simulation conducted to validate the proposed LDS. The aim is to provide a comprehensive analysis of the performance and effectiveness of the developed systems in two combat scenarios: Gotland and Palawan. By simulating the interactions between the suggested LDS, allied and adversary forces, the results offer insights into the capabilities and limitations of the LDS in achieving the desired objectives of GMBA, Establish Battlespace Denial, Establish Battlespace Control and Sustain Firepower.

To assess the effectiveness of the LDS, the MOEs derived previously were used as the metrics for evaluation. These MOEs provide a quantitative basis for analyzing the performance of the LDS in combat scenarios. The metrics for evaluation include percentage of all incoming threats detected within a specified period, percentage of RED forces killed, percentage of BLUE forces killed, and percentage of simulation runs when BLUE ammunition is depleted.

To simulate the performance of the LDS for each of the combat scenarios, 100 simulation runs were performed for both the baseline and modified systems. The results obtained were mixed with both gains and reductions across different aspects of system performance. This rest of the section details the team's analysis of the results as well as a comparison of system performance across scenarios. Table 11 shows the summary of the simulation results.

Table 11. Summary of Results

System Objectives	Evaluation Metrics (MOEs)	Objective	Palawan			Gotland		
			Baseline	Modified	Change	Baseline	Modified	Change
GMBA	**% Detected**	Maximize	8.62%	22.03%	Improve	96.11%	78.11%	Decline
Establish Denial	**% RED Killed**	Maximize	5.48%	1.67%	Decline	38.04%	13.37%	Decline
Establish Control	**% BLUE Killed**	Minimize	75.25%	43.38%	Improve	95.97%	2.62%	Improve
Sustain Firepower	**% runs BLUE ammo depleted**	Minimize	49.00%	0.00%	Improve	36.00%	0.00%	Improve

A. GOTLAND RESULTS

Based on the results from the Gotland scenario, a preliminary analysis suggests that unmanned platform systems demonstrated enhanced performance in the Establish Battlespace Control and Sustain Firepower top level functions. The baseline system exhibited an average platform destruction rate of 95.97%, whereas the modified system achieved a significantly lower average of 2.62%. However, in terms of the GMBA and Establish Battlespace Denial functions, the unmanned system displayed a reduced capacity compared to the systems employed by the two DDGs. While the baseline system had an average enemy target detection capability of 96.11%, the modified system demonstrated an average detection rate of 78.11%.

Based on these outcomes, it can be deduced that the unmanned system exhibits increased resilience as it sustains combat operations for a longer duration. By deploying a larger number of smaller platforms, the BLUE forces become more challenging to eliminate, ensuring a greater availability of weapons for continued use. Conversely, the modified system exhibited diminished detection capabilities and, correspondingly, experienced a decline in its ability to neutralize enemy platforms compared to the two DDGs. Preliminary analysis indicates that the inferior sensor detection capacities on the unmanned platforms were not adequately offset by the increased deployment of friendly platforms. A similar analysis can be applied to the system's capacity to destroy enemy platforms. The quantity of platforms employed by the modified system, along with their corresponding kill probability input data, proved insufficient to outperform the baseline system in terms of efficiency. The simulation results for both the baseline and modified systems for the Gotland scenario are presented in Tables 12 and 13.

Table 12. Simulation Results for Gotland (Baseline)

Run	% Detected	% RED Killed	% BLUE Killed	Blue Finished Ammo	Status	Result
1	93.671	32.911	94.521	0	5	Other Result (Weapon Sensor Mismatch Condition)
2	98.734	36.709	95.890	0	4	Red Out of All Weapons
3	94.937	30.380	91.781	0	5	Other Result (Weapon Sensor Mismatch Condition)
4	94.937	31.646	93.151	0	5	Other Result (Weapon Sensor Mismatch Condition)
5	92.405	40.506	95.890	1	3	Blue Out of All Weapons
6	94.937	43.038	94.521	0	4	Red Out of All Weapons
7	87.342	22.785	95.890	1	3	Blue Out of All Weapons
8	98.734	46.835	97.260	1	3	Blue Out of All Weapons
9	96.203	26.582	95.890	0	4	Red Out of All Weapons
10	91.139	36.709	94.521	0	4	Red Out of All Weapons
95	92.405	32.911	95.890	0	4	Red Out of All Weapons
96	96.203	37.975	97.260	0	4	Red Out of All Weapons
97	98.734	51.899	95.890	0	4	Red Out of All Weapons
98	96.203	32.911	94.521	0	4	Red Out of All Weapons
99	93.671	46.835	95.890	0	4	Red Out of All Weapons
100	93.671	39.241	94.521	0	4	Red Out of All Weapons
Avg	**96.11%**	**38.04%**	**95.97%**	**36.00%**		

Table 13. Simulation Results for Gotland (Modified)

Run	% Detected	% RED Killed	% BLUE Killed	Blue Finished Ammo	Status	Result
1	87.34	25.32	2.31	0	5	Other Result (Weapon Sensor Mismatch Condition)
2	88.61	15.19	3.06	0	5	Other Result (Weapon Sensor Mismatch Condition)
3	82.28	11.39	2.58	0	5	Other Result (Weapon Sensor Mismatch Condition)
4	97.47	20.25	3.38	0	5	Other Result (Weapon Sensor Mismatch Condition)
5	79.75	12.66	2.74	0	5	Other Result (Weapon Sensor Mismatch Condition)
6	74.68	11.39	2.95	0	5	Other Result (Weapon Sensor Mismatch Condition)
7	78.48	12.66	2.41	0	5	Other Result (Weapon Sensor Mismatch Condition)
8	86.08	21.52	2.20	0	5	Other Result (Weapon Sensor Mismatch Condition)
9	88.61	25.32	3.06	0	5	Other Result (Weapon Sensor Mismatch Condition)
95	81.01	15.19	3.38	0	5	Other Result (Weapon Sensor Mismatch Condition)
96	73.42	12.66	2.20	0	5	Other Result (Weapon Sensor Mismatch Condition)
97	82.28	7.59	2.63	0	5	Other Result (Weapon Sensor Mismatch Condition)
98	73.42	13.92	2.58	0	5	Other Result (Weapon Sensor Mismatch Condition)
99	69.62	11.39	1.98	0	5	Other Result (Weapon Sensor Mismatch Condition)
100	75.95	8.86	2.41	0	5	Other Result (Weapon Sensor Mismatch Condition)
Avg	**78.11%**	**13.37%**	**2.62%**	**0.00%**		

Detection and attrition of total assets for each side are given in percentages for each out of weapons in effort to quantify the Sustain Firepower system function, as indicated by a binary 1 in the ‘Blue Finished Ammo’ column; if BLUE still had ammunition at run termination, the program would report a 0. The ‘Status’ column also reports the reason which the program was terminated, which happens for a variety of reasons. Reports of a 1 or 2 indicate that all BLUE forces or RED forces, respectively, are completely eliminated.

Status codes of 3 or 4 indicate that BLUE or RED forces, respectively, have exhausted their ammunition supply. Finally, a status code 5 represents unique situations that are essentially stalemates, where either forces are unable to continue targeting the other forces. For example, if only sensor platforms and submerged assets from one side remain, they would be unable to target air forces from the other side. This scenario was not foreseen, where there were no more 'targetable' platforms, but assets still remained resulted in the simulation program continuing to run, with no end in sight. Adjustments were then made such that the program terminated when there were ten consecutive iterations of no targetable assets.

B. PALAWAN RESULTS

Upon analyzing the Palawan scenario results, it is evident that the system incorporating unmanned platforms demonstrated notable improvements in the functions of GMBA, Establish Battlespace Control, and Sustain Firepower. However, in terms of the Establish Battlespace Denial function, the modified system exhibited reduced efficiency compared to the two DDGs. While the old system achieved an average enemy target detection rate of 8.62%, the new system detected an average of 22.03% of the same targets. Moreover, a positive result was observed in terms of the percentage of BLUE forces eliminated. The system comprising the two DDGs achieved an average platform destruction rate of 75.25%, whereas the modified system achieved an average of 43.38%. Notably, another improvement was observed in the context of the Winchester condition, where friendly forces exhaust all weapons. While this condition occurred approximately 49% of the time when using the two DDGs, it was completely absent when employing the system comprised of unmanned platforms.

Upon initial analysis, the outcomes from the Palawan scenario exhibited a similar positive trend regarding the system's resilience, which aligns with the reasons mentioned in the previous scenario analysis. However, a significant distinction was observed as the introduction of unmanned systems resulted in an enhanced detection capability when compared to the two DDGs. This indicates that a more distributed force in the combat scenario can offset the individual lower detection capability of smaller platforms.

Nevertheless, this compensation did not effectively translate into a lower attrition rate for the RED forces. Once again, the number of unmanned platforms utilized failed to adequately compensate for the limited payload capacity of the smaller to medium-sized platforms. Simulation results for both the baseline and modified systems for the Palawan scenario are presented in Tables 14 and 15.

Table 14. Simulation Results for Palawan (Baseline)

Run	% Detected	% RED Killed	% BLUE Killed	Blue Finished Ammo	Status	Result
1	7.02	6.20	62.50	0	5	Other Result (Weapon Sensor Mismatch Condition)
2	9.92	6.20	62.50	0	5	Other Result (Weapon Sensor Mismatch Condition)
3	11.57	7.02	62.50	0	5	Other Result (Weapon Sensor Mismatch Condition)
4	8.68	4.96	87.50	1	3	Blue Out of All Weapons
5	7.85	6.20	62.50	0	5	Other Result (Weapon Sensor Mismatch Condition)
6	8.68	6.61	62.50	0	5	Other Result (Weapon Sensor Mismatch Condition)
7	6.61	4.13	87.50	1	3	Blue Out of All Weapons
8	7.85	6.20	62.50	0	5	Other Result (Weapon Sensor Mismatch Condition)
9	7.85	2.48	100.00	1	1	All Blue Killed
10	7.85	4.96	87.50	1	3	Blue Out of All Weapons
95	7.85	6.20	62.50	0	5	Other Result (Weapon Sensor Mismatch Condition)
96	8.68	5.37	87.50	1	3	Blue Out of All Weapons
97	7.02	4.13	75.00	1	3	Blue Out of All Weapons
98	11.57	6.61	87.50	0	5	Other Result (Weapon Sensor Mismatch Condition)
99	11.98	6.61	62.50	1	3	Blue Out of All Weapons
100	8.26	6.20	75.00	1	3	Blue Out of All Weapons
Avg	**8.62%**	**5.48%**	**75.25%**	**49.00%**		

Table 15. Simulation Results for Palawan (Modified)

Run	% Detected	% RED Killed	% BLUE Killed	Blue Finished Ammo	Status	Result
1	22.73	1.65	43.10	0	5	Other Result (Weapon Sensor Mismatch Condition)
2	22.73	2.48	44.56	0	5	Other Result (Weapon Sensor Mismatch Condition)
3	28.10	2.07	43.44	0	5	Other Result (Weapon Sensor Mismatch Condition)
4	18.18	0.83	42.59	0	5	Other Result (Weapon Sensor Mismatch Condition)
5	19.42	0.83	44.90	0	5	Other Result (Weapon Sensor Mismatch Condition)
6	26.03	2.07	41.90	0	5	Other Result (Weapon Sensor Mismatch Condition)
7	26.45	3.31	44.90	0	5	Other Result (Weapon Sensor Mismatch Condition)
8	16.12	0.83	43.96	0	5	Other Result (Weapon Sensor Mismatch Condition)
9	19.42	1.65	43.44	0	5	Other Result (Weapon Sensor Mismatch Condition)
10	21.49	0.83	44.90	0	5	Other Result (Weapon Sensor Mismatch Condition)
95	25.62	1.65	44.99	0	5	Other Result (Weapon Sensor Mismatch Condition)
96	22.73	0.83	41.30	0	5	Other Result (Weapon Sensor Mismatch Condition)
97	26.45	2.48	44.47	0	5	Other Result (Weapon Sensor Mismatch Condition)
98	24.79	4.13	46.02	0	5	Other Result (Weapon Sensor Mismatch Condition)
99	16.94	1.24	40.19	0	5	Other Result (Weapon Sensor Mismatch Condition)
100	20.25	2.89	46.53	0	5	Other Result (Weapon Sensor Mismatch Condition)
Avg	**22.03%**	**1.67%**	**43.38%**	**0.00%**		

C. ANALYSIS

It is initially paramount to revisit the rationales behind examination of the two distinct scenarios. As previously discussed, when analyzing the results of different scenarios, a more comprehensive analysis becomes feasible as it enables the evaluation of the system against diverse types of threats and platforms characterized by distinct attributes.

The merits and drawbacks of the proposed system became evident upon examining the outcomes of the Gotland and Palawan scenarios. A clear advantage was observed in the enhanced performance of desired resilience attributes, particularly in evaluating the Establish Battlespace Control and Sustain Firepower functions. This positive outcome can be attributed to the optimized deployment of unmanned platforms, which created a distributed network of sensors. This characteristic can be effectively utilized as a deterrence mechanism, as it necessitates a more significant adversary effort to disrupt such a complex system.

However, the inferior capabilities of on-board sensors and the limited payload capacity of unmanned platforms remained significant disadvantages when it came to detecting and neutralizing enemy platforms when compared to the two DDGs. Even with the concept of deploying a larger quantity of BLUE force platforms, it was insufficient to match the inherent capabilities of a more robust platform while working within the same cost constraints.

Another aspect to consider is the distinction in casualty outcomes between the different systems for the BLUE forces. The system composed of the two DDGs is associated with crew casualties, whereas the unmanned system primarily incurs platform losses. The cost incurred in terms of human lives is immeasurable in nature. The proposed system, although exhibiting lower lethality, presents a reduced risk of casualties for warfighters in the BLUE forces.

However, the incorporation of unmanned platforms with enhanced detection capabilities and larger payload capacities would provide the BLUE forces with a more extensive network of sensors and weapons. This would enable them to establish a formidable presence while minimizing the risk of unintended harm to warfighters, fostering a distributed force concept.

One aspect of these modeling results and analysis that may require further examination during future work is the sensitivity aspects of these results. During the analysis of these results, the team discussed the possibility that these results may be sensitive to small changes in the initial number of units. Further sensitivity analysis of these different LDSs is desired however due long computational run time of the combat model, it was determined that systematic running of this model simulation to test for changes in the initial parameters was unfeasible given the scope of this project.

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XII. CONCLUSION

Our project tasking was to create a LDS. We worked toward this goal using a systems engineering approach by liaising with our stakeholders, determining key functions, identifying candidate platforms, optimizing those platforms, and monitoring the results. In this section the overall project conclusion will be discussed including overall project recommendations and possible future work.

A. OVERALL PROJECT CONCLUSION

The SE process has proven able to accommodate further military research. Through the process, we have developed an iterative approach to force design that can serve the Navy through the next decade at a minimum. We have further laid the groundwork for development of new platforms and capabilities through a function-based approach that seeks to optimize platforms for a given role rather than have one platform do everything.

Given the project's high level of scope, we tried to be as accurate as possible when it came to the modeling and simulation of our LDS. Multiple factors, however, such as the unclassified nature of the project, limited performance metric availability, and the modeling language used, challenged our team to maximize the project's full potential. However, we were able to show that changing the weighting of the functions and domain importance produced optimized systems for specific mission sets or geographic locations.

Other realizations include weapon capacity limitations continue to be a factor in the lethality of our designs. As shown, we were able to increase our battlespace awareness, control, and sustainment metrics, however, the denial metric, attributed as lethality, was diminished in both scenarios from our initial two DDG force. We suspect that the lack of missile capacity on each individual platform and the prohibitive cost of modern weaponry caused the optimization tool to purchase less capable platforms to meet the cost requirements. If the cost of weapons can be reduced, we believe that a distributed and lethal force is possible.

B. PRODUCT RECOMMENDATIONS

The primary finding the team found, and our recommendation moving forward, involves the efficiency of small unmanned systems. Their use allowed us to sense and track targets effectively within large areas, with two or three levels of redundancy. They also allowed us to distribute weapons and lethality instead of concentrating firepower in easily targetable vessels. Our designed LDSs were able to compete at lethality levels at or near those of legacy systems while remaining cheaper, more attritable, and distributed. Our recommendation is that the DOD acquire unmanned systems capable of directly engaging targets to take advantage of this finding.

To make the most out of the project, the team recommends moving it to the classified level. Doing so would allow more accurate information to be used for the optimization tool input. A significant team concern was that some of the tactical inputs were estimated or assumed to comply with the unclassified nature of the project. We were therefore starting off with potentially inaccurate data which may have led to suboptimal recommendations by the optimization tool. From there, the R model could have been working with the same questionable data, which may have contributed in part to the results being less than promising. The optimization tool has the potential, if refined, to greatly aid in future force design decisions. However, its output is only as accurate as the data put into it. Moving the research into a classified realm would allow our project to be used to the fullest capacity and allow for less assumptions to affect the results.

The team also recommends more robust models be utilized to evaluate the recommendations of the optimization tool. The R software is adequate for simplified modeling, but somewhat rudimentary. It envisions each engagement as a discrete event and does not take individual action, doctrine, or simultaneous engagements into consideration. To take the project further, the team recommends an agent-based model be used. This should allow for better modeling of human behavior, doctrine, and tactics to be utilized for a more realistic depiction of how the system would function in a combat environment. Weaponry such as mines would also be better tested as they are more likely to affect decision making rather than making a continual impact on enemy forces during combat.

Additionally, an agent-based system would allow the model to be tested across the combat continuum.

Finally, the team recommends refining the MOEs used to measure the success of the system. By confining denial and control to RED and BLUE forces killed respectively, the model does not take into account whether or not the RED force was denied access to a specific geographic area. Therefore, the team was unable to state whether or not the system was successful in denying an enemy space, only whether or not the system is capable of inflicting casualties.

C. PROCESS RECOMMENDATIONS

The team recommends the following to improve the process of choosing candidate systems in the future. First, we recommend the DOD create a database of unmanned systems, as these assets are promising platforms that will be integrated into existing force structure. During the project, it was sometimes hard to find detailed information on which unmanned systems are currently being used in the field or being developed by the U.S. or technology-focused companies. To effectively develop networks of unmanned systems across domains, systems engineers would be aided by a database of fieldable systems. Valuable information for the list includes cost, endurance, weapon capabilities, and capacity for upgrades. Having this system would allow for a decrease in the procurement time of COTS systems. The team also recommends adopting value scoring for unmanned systems under test and those being considered for future use by the DOD. Doing so would allow commanders and program managers to quickly assess the relative strengths and weaknesses of a large number of unmanned systems, as well as their relative comparisons to manned platforms.

D. FUTURE WORK

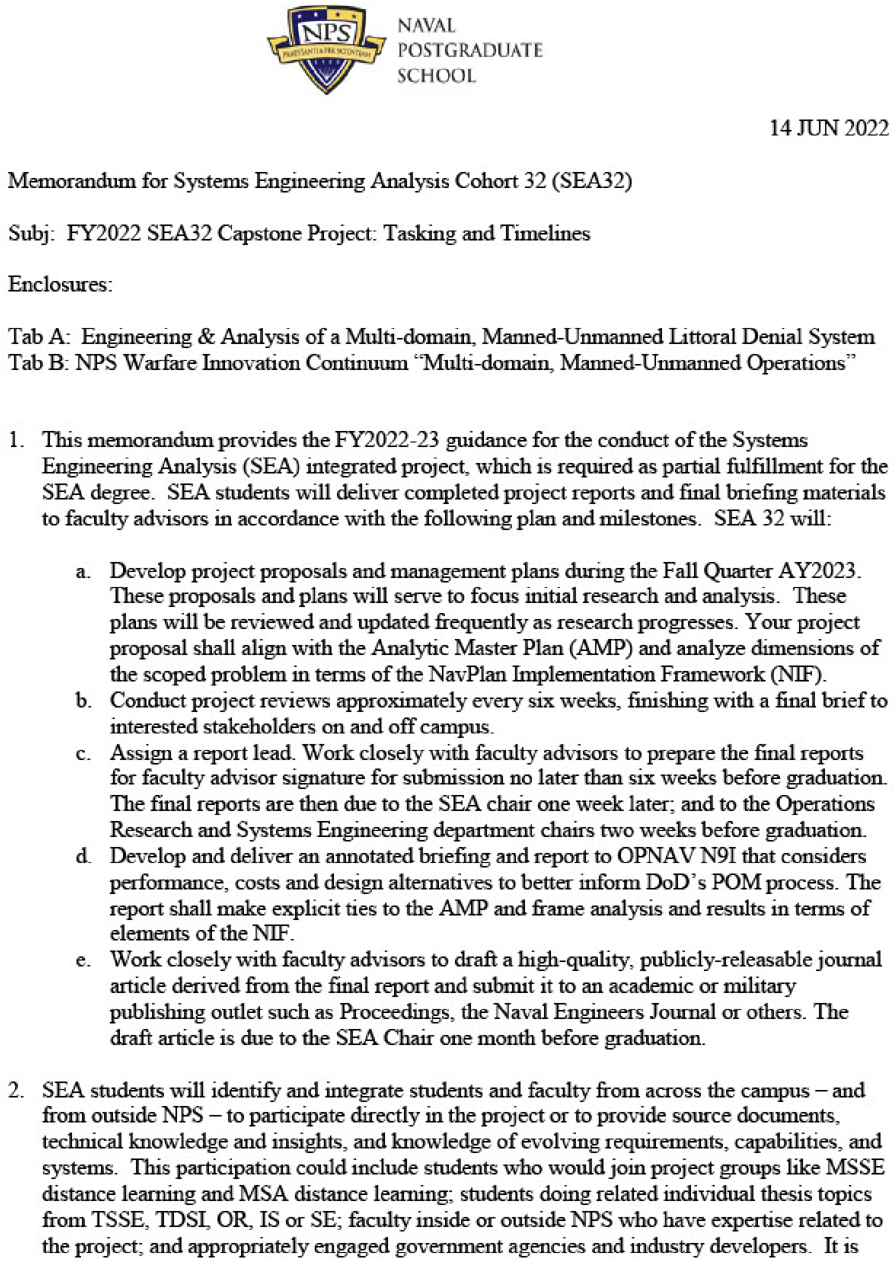
The methodology and practices utilized in system engineering and operational analysis literature were instrumental in achieving the results presented in this work. The proposed model for optimizing systems, as well as other models of this nature, heavily relies on input data such as the detection distances and speeds of the platforms being studied. Similarly, the model for calculating the attrition between two platforms is highly dependent on the kill probabilities of the combat being analyzed. Due to its unclassified nature, the project lacked more accurate data from the platforms that were deemed confidential. However, a group with higher authorization to access confidential data could utilize the same models suggested in this work with more precise input data than what is available in open-source publications.

Additionally, the results obtained from this project could be further applied by comparing the system resulting from the proposed process with other groups of systems. In the case of this project, two DDGs were chosen as a group of systems to compare with the resultant LDS. However, more thorough operational analyses may suggest that the LDS should be evaluated against another group of systems to determine its effectiveness.

Another potential application of the optimization and attrition model proposed in this project would be to narrow the scope and optimize systems for a specific type of action related to littoral denial. For instance, the model could be utilized to compare the effectiveness of underwater mine delivery systems or air defense systems. By doing so, a more focused and tailored approach to system optimization could be achieved.

While the project's initial endeavor yielded some fundamental findings, it is essential to recognize that a more thorough examination may be required to address the identified deficiencies of the proposed system. The fact that the optimized system of systems did not achieve the desired effectiveness during the analysis of the top-level function of Establish Battlespace Denial, for example, indicates that these functionalities may warrant further dedicated analysis. Therefore, a more comprehensive examination of battlespace denial subfunction actions may be needed to further system improvement.

APPENDIX A. MEMORANDUM FOR SYSTEMS ENGINEERING ANALYSIS COHORT 32 (SEA 32)



NAVAL
POSTGRADUATE
SCHOOL

14 JUN 2022

Memorandum for Systems Engineering Analysis Cohort 32 (SEA32)

Subj: FY2022 SEA32 Capstone Project: Tasking and Timelines

Enclosures:

Tab A: Engineering & Analysis of a Multi-domain, Manned-Unmanned Littoral Denial System
Tab B: NPS Warfare Innovation Continuum "Multi-domain, Manned-Unmanned Operations"

1. This memorandum provides the FY2022-23 guidance for the conduct of the Systems Engineering Analysis (SEA) integrated project, which is required as partial fulfillment for the SEA degree. SEA students will deliver completed project reports and final briefing materials to faculty advisors in accordance with the following plan and milestones. SEA 32 will:

    a. Develop project proposals and management plans during the Fall Quarter AY2023. These proposals and plans will serve to focus initial research and analysis. These plans will be reviewed and updated frequently as research progresses. Your project proposal shall align with the Analytic Master Plan (AMP) and analyze dimensions of the scoped problem in terms of the NavPlan Implementation Framework (NIF).
    b. Conduct project reviews approximately every six weeks, finishing with a final brief to interested stakeholders on and off campus.
    c. Assign a report lead. Work closely with faculty advisors to prepare the final reports for faculty advisor signature for submission no later than six weeks before graduation. The final reports are then due to the SEA chair one week later; and to the Operations Research and Systems Engineering department chairs two weeks before graduation.
    d. Develop and deliver an annotated briefing and report to OPNAV N9I that considers performance, costs and design alternatives to better inform DoD's POM process. The report shall make explicit ties to the AMP and frame analysis and results in terms of elements of the NIF.
    e. Work closely with faculty advisors to draft a high-quality, publicly-releasable journal article derived from the final report and submit it to an academic or military publishing outlet such as Proceedings, the Naval Engineers Journal or others. The draft article is due to the SEA Chair one month before graduation.

2. SEA students will identify and integrate students and faculty from across the campus – and from outside NPS – to participate directly in the project or to provide source documents, technical knowledge and insights, and knowledge of evolving requirements, capabilities, and systems. This participation could include students who would join project groups like MSSE distance learning and MSA distance learning; students doing related individual thesis topics from TSSE, TDSI, OR, IS or SE; faculty inside or outside NPS who have expertise related to the project; and appropriately engaged government agencies and industry developers. It is

the students' responsibility to integrate the efforts of outside participants in the projects. Faculty advisors and the SEA Chair will assist in these efforts.

3. Prior to commencing the formalized systems engineering and analysis process including stakeholder analysis, **the SEA team will consult with Dr. Larry Shattuck, Chairman of the NPS Institutional Review Board and submit to him**, a general description of the team's systems and analytical approach to address the tasking and a list of candidate questions for stakeholders to Dr. Shattuck to review. The intent is to ensure questions are oriented about the "what" of the systems and not about the "who" of the stakeholder.

4. The analysis will employ the systems engineering and operations analysis methodologies presented in class work and from the project advisors. The role of the SEA students is that of the lead project systems engineering team, working closely with other members of the project engineering teams from TDSI and other campus curricula. SEA students will be expected to define the functions and performance of systems, develop alternative architectures to meet those functions, and evaluate the alternative architectures for performance and cost. In executing these tasks, students will be defining and understanding the overall project requirements, recognizing that the definition process is iterative and will evolve as the project progresses.

5. Grades are assigned to the participants in these projects. Although work is performed as part of a team, individual performance will be the basis for this evaluation. Successful completion and documentation of the project is a degree requirement.

6. The SEA 32 project will build on, possibly challenge, but not replicate, other DOD, Navy, Naval War College, FFRDC, MSSE and SEA projects. SEA 32 will coordinate their study efforts, participate and occupy leadership roles in other FY2/23 efforts at NPS aimed at contributing to developing the concepts and designs for preparing for war in the era of Great Power Competition and unmanned systems warfare. These activities, coordinated within the Naval Warfare Studies Institutes' research task forces and campaign of analyses are described in Tab B.

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Distribution: SEA 32 students; NPS Warfare Chairs; Profs. Huang, Papoulias, Carlyle, Yakimenko, Alderson, Eisenberg, Stevens, Kline, Brutzman, Buettner, McDowell, Shattuck; President Rondeau; Provost Gartner; Dean Smith, CDR Arledge; RDML Williams, VADM Lewis, VADM Sawyer, RADM Pitts (OPNAV N9I), Mr. Hootman (OPNAV N9IB), CAPT Davis (N9IX), Ms. Ballard (N9X1), Ms. Virginia Beall (N81B), VADM Conn (OPNAV N9), Mr. Lluy (OPNAV N9B), Mr. Werchado (USMC ADC, P&R), Ms. Englehorn, and Ms. Cain

TAB A

SEA 32 Tasking
Engineering and Analysis of a Multi-domain, Manned-Unmanned Littoral Denial System

Building on the SEA 31 project, and reaping lessons learned from all the NWSI research task forces and campaign of analyses activities, SEA 32 will focus on "Engineering and Analysis of a Multi-domain, Manned-Unmanned Littoral Denial System". Using principles from your coursework, augmented with your warfighting experiences, develop a proposal for an operational concept, operational analysis, architecture, and detailed design of a *non-platform centric*, system of systems, multi-domain, manned-unmanned littoral denial system for a specified scenario and mission of your choice.

Your system will need to address countering all level of threats: air, surface, and sub-surface while being hardened to threats from cyber and electronic warfare. It may also provide decoy services, and could incorporate a network of mobile mines or other future capabilities and concepts. The multi-domain manned-unmanned littoral denial system should encompass its own ISR, non-kinetic and/or kinetic weapons, and BDA; however, these capabilities could and should be generated by a network of small, risk-worthy, manned-unmanned systems (i.e.: NOT platform centric; think more like an Aegis system).

Missions might include Full Spectrum ASW; Littoral Warfare (Strike); War at Sea Strike (Long Range Fires); Port/Base Security; Integrated Air and Missile Defense; Maritime Interdiction Operations (Grey Zone activities); Protection of Underwater Infrastructures; or others. To the greatest extent possible, SEA 32 should seek to identify areas of utility and synergy across all mission-areas, meaning: if a different mission where to be executed, your system should be able to adapt.

Note, the instantiated system design, and mission analyses, will be geographically and mission dependent. For example, ensuring the security of sea approaches to Singapore may call for a different system configuration (interchangeable elements and connections), to address littoral and coastal waters, than denying access to the Philippine Sea through the Luzon Strait, which would be different from grey zone activities in the Baltic Sea.

As you develop your scenario, you are referred to the Marine Corps EABO concept, the Navy's DMO concept, and Hybrid Force 2045 for inspiration. Overarching concepts described in the CNO NAVPLAN, NWP-3, Unmanned Campaign Plan, Operational Overmatch, the Analytic Master Plan, the NAVPLAN Integration Framework, and other guidance direct the basis of force development and deployment, and should be understood, referenced, and integrated into your work. If your system does not support and enable these, it is irrelevant. SEA 32 may use the NSWC Mission Engineering approach to describe the functional requirements, networks, and system of small, manned-unmanned, risk-worthy systems, as well as to implement analyses of the same. SEA 32 will use principles from systems engineering and operations research to develop operational concepts, identify future force requirements, capability gaps, and an architecture to meet those requirements, as well as to frame, inform and execute detailed design.

SEA 32 should anticipate an evolving threat; therefore, it is reasonable to envision that China and Russia employ many more unmanned systems, and that their technology will equal or exceed ours. Furthermore, anticipate increased grey zone or other activities short of war. Focus on peer threats who are emboldened to execute on their National aims by all means at their disposal, inclusive of non-military assets and actions. Your timeframe for your analysis is the next ten years.

The overall goal is to perform disciplined analyses of critical warfighting functions (shoot, maneuver, defend, and resupply) implement with enablers (unmanned, networks, live-virtual-constructed training, and artificial intelligence) to gain meaningful insights for a future scenario. Doing so will tie your work to the NIF and AMP as illustrated in Figure 1.

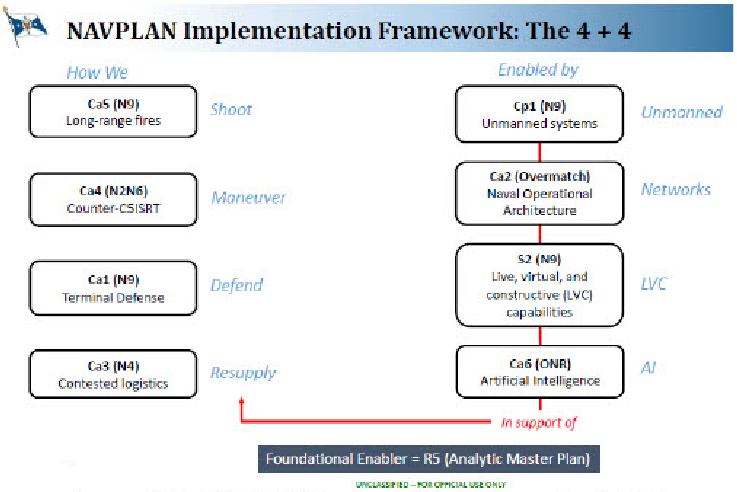

Figure 1. The NAVPLAN Implementation Framework or “4+4”.

Advisors:
    Dr. Fotis Papoulias, Systems Engineering Department
    Dr. Jefferson Huang, Operations Research Department
On Campus Subject Matter Experts:
    NPS Warfare Chairs
    VADM David Lewis, USN (ret), Director, Naval Warfare Studies Institute
    VADM Phillip Sawyer, USN (ret), Undersea Warfare Chair
    RDML Rick Williams, USN (ret), Mine Warfare Chair
    CAPT Jeff Kline, USN (ret), Professor of Practice
    Col Todd Lyons, USMC (ret)
    CDR Matt Geiser, USN
Off Campus Points of Contact:
    CAPT Wayne Porter, USN (ret)
    CDR Harrison Schramm, USN (ret)

TAB B

NPS Warfare Innovation Continuum
A Coordinated Naval Postgraduate School Cross-Campus Project FY 22-23
"Multi-domain, Manned-Unmanned Operations"

Purpose: This paper's purpose is to the FY22-FY23 NPS NWSI Warfare Innovation Continuum (WIC) theme to be "Multi-domain, Manned-Unmanned Operations" to align with the CNO's NAVPLAN, the Tri-Service Maritime Strategy "Advantage at Sea", and the Navy's Analytic Master Plan.

Background: For the past 13 years the NPS has adopted a major theme of naval interest to align over 300 faculty and students' classroom, research, and capstone project work with emerging technologies, naval concepts and operational issues under the name Warfare Innovation Continuum. NWSI has adopted the spirit of this collaboration but reoriented these efforts to various focused collaborative research and education activities under research task forces. The three current research groups are Task Force Overmatch, Task Force Maritime Gray Zone, and Task Force Hybrid Force 2045. These task forces capture a series of independent, but coordinated cross-campus educational and research activities to provide insight into the opportunities for warfighting in the complex and electromagnetically contested environment at sea and in the littorals. Products from these efforts often precede and contribute to warfare development centers' concept development campaigns.[i] In this sense, NPS fulfills its mission to provide a graduate education experience to prepare our officers for uncertain conflict environments as technological leaders.

Discussion: Emerging technologies in unmanned systems; directed energy; autonomy; missile systems; undersea systems; long-range, netted, quantum and multi-domain sensors; additive manufacturing; artificial intelligence, and networks create a new environment for operations in the littorals, on, under and over the sea. This changing technology environment both challenges traditional fleet operations and provides opportunities for new fleet design; innovative tactics, techniques, and procedures to achieve multi-domain objectives in sea control, power projection and distributed maritime operations. Unmanned systems technologies; joint, combined and coalition forces contributions; and multi-domain C2 provide opportunities to support integrated offensive operations, and further develop a hybrid naval force to operate in the range from competition to conflict. As a graduate education and research center committed to gaining technological advantage, NPS is a fertile ground for exploring opportunities to advance force design.

Proposal: Designate "Multi-domain, Manned-Unmanned Operations" as the NPS SEA theme for FY22-FY23 to contribute to all the NWSI research task force efforts, but particularly Hybrid Force 2045. The SEA cross campus project will contribute, and be informed by, the Navy's AMP events and studies as it progresses. For example, issues from NWC wargaming may shape the SEA study efforts while in progress.

The larger research questions for this continuum are: "**How might a *non-platform centric*, multi-domain, manned-unmanned system of systems, and new operational concepts, and alternative fleet designs for the same, contribute to a more effective naval force across the spectrum from competition to conflict?"**

In alignment with the Tri-Service Maritime Strategy and CNO's NAVPLAN and to support the Navy's Analytical Master Plan and Marine Corp's Force Design, the following NWSI campaign of analyses activities are proposed:

- NWSI research group Task Force Overmatch supports NAVWAR's efforts on Naval Operational Architecture Development
- Faculty submitting IREPs to the NPS Naval Research Program align their proposals to the CNOG's key operational problems (with no reference) and/or hybrid force development
- Capstone Courses like the Wargaming, Joint Campaign Analysis, Joint C4I, Tactical Oceanography, Naval Tactical Analysis, and others adopt a common unclassified world-wide conflict scenario and address topics related to a "Multi-domain, Manned-Unmanned Operations," and those emerging technologies which may enable it. Specific technical or tactical/operational topics maybe subjects for sponsored wargames. In addition, the OPNAV N9I would like to better understand how wargaming data could be captured, automatically parsed, and automatically reported to support rapid innovation.
- The NPS NWSI September Warfare Innovation Workshop brings together naval systems commands and navy lab engineers; fleet representatives; warfare center and warfare development center representatives; warfare development squadrons, NEE faculty and students; and industry engineers to consider emerging technology opportunities on Multi-domain, Manned-Unmanned Operations.
- Incoming students within the Master of Science in Strategy program will be directed to focus their applied research thesis towards topics related to a "Multi-domain, Manned-Unmanned Operations" and those emerging technologies may enable it.
- The NPS Total Ship Systems Engineering design an unmanned-manned surface vessel or platform, or portion thereof, in a three-course engineering design sequence.
- The three-quarter NPS Systems Engineering Analysis interdisciplinary cross campus capstone project adopt "Multi-domain, Manned-Unmanned Operations" to explore force architecture design alternatives.
- CRUSER, CISER, JIFX, and the various research centers on campus are made aware of the broad WIC topic and contribute to the final executive report

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[i] 2013-2014 WIC theme is "Distributing Air and Future Naval Forces" In January 2015 Surface Force proposes "Distributed Lethality" which USFF modifies in 2016 as the concept "Distributed Maritime Operations" Capstone projects (TSSE, JCA, and J4CI classes) and theses produced preceding these concepts and later in support of developing these concepts.

2014-2015 WIC theme is "Littoral Warfare in the Contested Environments" In 2015 the concept of "Littoral Operations in the Contested Environments" is proposed by NWDC and MWCL. NPS work fed directly into that proposal

2019-2020 WIC theme is "Logistics in Contested Environments", now a major study project by OPNAV N4, NWDC, and MCWL. NPS work includes analysis starting in FY18, the TSSE group design for a robust logistics carrier, and the SEA group interdisciplinary project with the same title. All provided to OPNAV N4, NWDC, and MCWL

APPENDIX B. STAKEHOLDER SURVEY

SEA 32 Sponsor Survey Questions

1. How effective would U.S. forces be operating in denied comms (enemy imposed or self-imposed) environment in 2033?
    a. Not at all
    b. Somewhat
    c. Very
    d. Extremely
2. Rank the following missions in priority order for an anti-access, area-denied environment. (1 highest priority)
    a. USW
    b. Surface Combat
    c. Strike
    d. Air Combat
    e. Other ________________________
3. Rank the following platforms in priority order for conducting swarm operations in an anti-access, area-denied environment. (1 highest priority)
    a. Unmanned Air
    b. Unmanned Surface
    c. Manned Platform
    d. Other _________________________
4. How prevalent will cyber-attacks by China be on allied satellite infrastructure by 2033?
    a. Not at all prevalent
    b. Somewhat prevalent
    c. Very prevalent
    d. Extremely prevalent
5. How prevalent will cyber-attacks by Russia be on allied satellite infrastructure by 2033?
    a. Not at all prevalent
    b. Somewhat prevalent
    c. Very prevalent
    d. Extremely prevalent
6. Which is going to be the most likely Chinese area of effect for electronic warfare attacks by 2033?
    a. Point (single unit or strike group)

    b. Local (single sector or area)
    c. Widespread (Entire OA i.e. South China Sea)
    d. Greater than widespread (entire theater)
7. Which is going to be the most likely Russian area of effect for electronic warfare attacks by 2033?
    a. Point (single unit or strike group)
    b. Local (single sector or area)
    c. Widespread (Entire OA i.e. Baltic Sea)
    d. Greater than widespread (entire theater)
8. How feasible are adversary directed energy attacks to be by 2033?
    a. Not at all feasible
    b. Somewhat feasible
    c. Very feasible
    d. Extremely feasible
9. How effective will USN submarines be in the event of conflict in the Baltic Sea?
    a. Ineffective
    b. Low
    c. Moderate
    d. High
10. Rank the following homing methods by order of likelihood for U.S. force's shore-based anti-ship missiles?
    a. Active
    b. Semi-active / third party
    c. Passive
11. What would the most preferred projection modality be for logistics?
    a. Manned air platforms
    b. Unmanned air platforms
    c. Manned surface platforms
    d. Unmanned surface platforms
12. How feasible are autonomous/semi-autonomous logistical vehicles by the year 2033?
    a. Infeasible
    b. Unlikely
    c. Feasible
    d. Likely
13. If answered C or D for the above question, rank the following types of vehicles by maturity/feasibility (1 being the most mature and feasible):

    a. Surface
    b. Sub-surface
    c. Land-based
    d. Aerial
14. What is the feasibility for allied relative position missile targeting by 2033?
    a. Infeasible
    b. Unlikely
    c. Feasible
    d. Likely
15. Rank the following platforms in priority for conducting strike missions during littoral denial operation.
    a. Aircraft
    b. Surface Ship
    c. Submarine
    d. Unmanned
16. For a Joint air superiority mission with allied nations, rank the following methods of sharing positioning information between air assets. (1 highest priority)
    a. Radar
    b. Data Link
    c. Satellite Data Link
    d. Other ________________________

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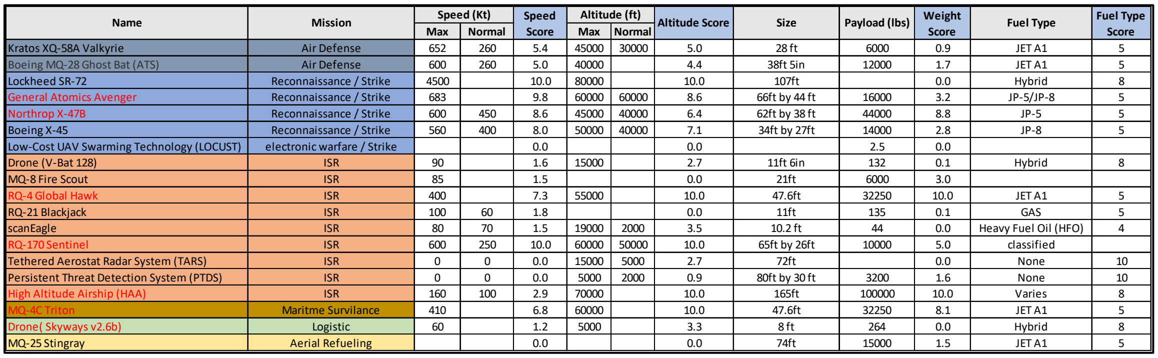
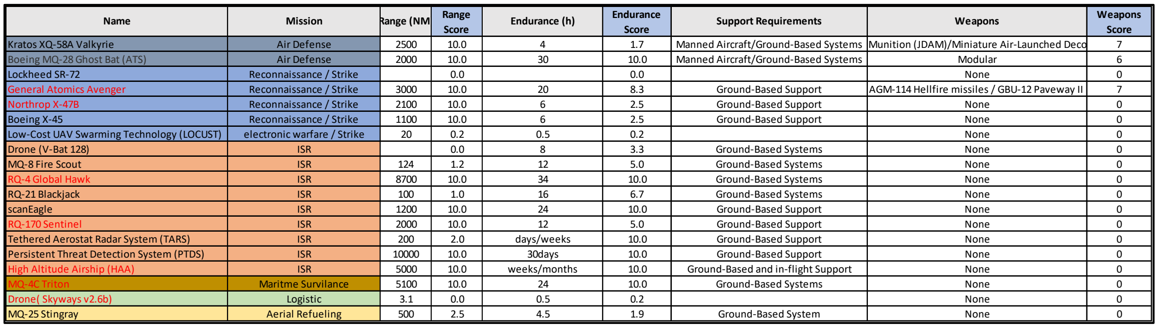
APPENDIX C. UNMANNED PLATFORM SCORING

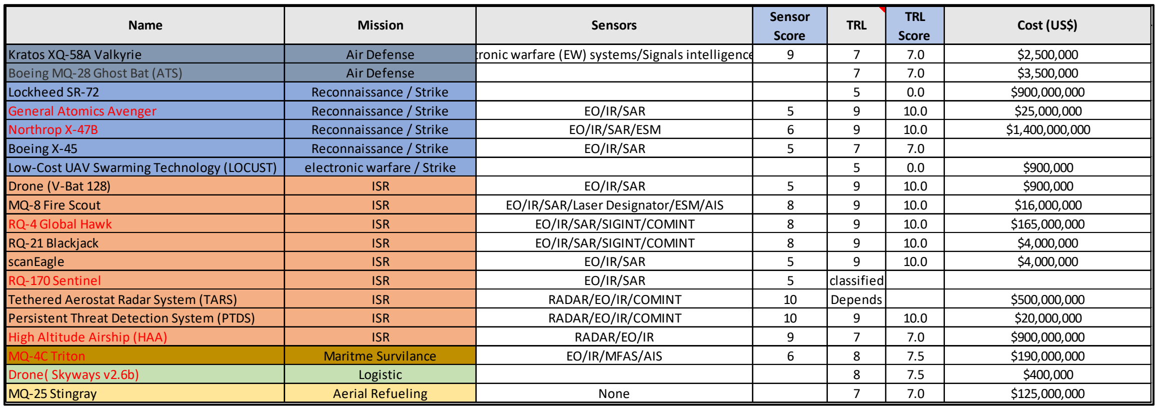
Table 16. Value Scoring of Air Platforms



Name	Mission	Speed (Kt)		Speed Score	Altitude (ft)		Altitude Score	Size	Payload (lbs)	Weight Score	Fuel Type	Fuel Type Score
		Max	Normal		Max	Normal						
Kratos XQ-58A Valkyrie	Air Defense	652	260	5.4	45000	30000	5.0	28 ft	6000	0.9	JET A1	5
Boeing MQ-28 Ghost Bat (ATS)	Air Defense	600	260	5.0	40000		4.4	38ft 5in	12000	1.7	JET A1	5
Lockheed SR-72	Reconnaissance / Strike	4500		10.0	80000		10.0	107ft		0.0	Hybrid	8
General Atomics Avenger	Reconnaissance / Strike	683		9.8	60000	60000	8.6	66ft by 44 ft	16000	3.2	JP-5/JP-8	5
Northrop X-47B	Reconnaissance / Strike	600	450	8.6	45000	40000	6.4	62ft by 38 ft	44000	8.8	JP-5	5
Boeing X-45	Reconnaissance / Strike	560	400	8.0	50000	40000	7.1	34ft by 27ft	14000	2.8	JP-8	5
Low-Cost UAV Swarming Technology (LOCUST)	electronic warfare / Strike			0.0			0.0		2.5	0.0		
Drone (V-Bat 128)	ISR	90		1.6	15000		2.7	11ft 6in	132	0.1	Hybrid	8
MQ-8 Fire Scout	ISR	85		1.5			0.0	21ft	6000	3.0		
RQ-4 Global Hawk	ISR	400		7.3	55000		10.0	47.6ft	32250	10.0	JET A1	5
RQ-21 Blackjack	ISR	100	60	1.8			0.0	11ft	135	0.1	GAS	5
scanEagle	ISR	80	70	1.5	19000	2000	3.5	10.2 ft	44	0.0	Heavy Fuel Oil (HFO)	4
RQ-170 Sentinel	ISR	600	250	10.0	60000	50000	10.0	65ft by 26ft	10000	5.0	classified	
Tethered Aerostat Radar System (TARS)	ISR	0	0	0.0	15000	5000	2.7	72ft		0.0	None	10
Persistent Threat Detection System (PTDS)	ISR	0	0	0.0	5000	2000	0.9	80ft by 30 ft	3200	1.6	None	10
High Altitude Airship (HAA)	ISR	160	100	2.9	70000		10.0	165ft	100000	10.0	Varies	8
MQ-4C Triton	Maritme Survilance	410		6.8	60000		10.0	47.6ft	32250	8.1	JET A1	5
Drone(Skyways v2.6b)	Logistic	60		1.2	5000		3.3	8 ft	264	0.0	Hybrid	8
MQ-25 Stingray	Aerial Refueling			0.0			0.0	74ft	15000	1.5	JET A1	5



Name	Mission	Range (NM	Range Score	Endurance (h)	Endurance Score	Support Requirements	Weapons	Weapons Score
Kratos XQ-58A Valkyrie	Air Defense	2500	10.0	4	1.7	Manned Aircraft/Ground-Based Systems	Munition (JDAM)/Miniature Air-Launched Deco	7
Boeing MQ-28 Ghost Bat (ATS)	Air Defense	2000	10.0	30	10.0	Manned Aircraft/Ground-Based Systems	Modular	6
Lockheed SR-72	Reconnaissance / Strike		0.0		0.0		None	0
General Atomics Avenger	Reconnaissance / Strike	3000	10.0	20	8.3	Ground-Based Support	AGM-114 Hellfire missiles / GBU-12 Paveway II	7
Northrop X-47B	Reconnaissance / Strike	2100	10.0	6	2.5	Ground-Based Support	None	0
Boeing X-45	Reconnaissance / Strike	1100	10.0	6	2.5	Ground-Based Support	None	0
Low-Cost UAV Swarming Technology (LOCUST)	electronic warfare / Strike	20	0.2	0.5	0.2		None	0
Drone (V-Bat 128)	ISR		0.0	8	3.3	Ground-Based Systems	None	0
MQ-8 Fire Scout	ISR	124	1.2	12	5.0	Ground-Based Systems	None	0
RQ-4 Global Hawk	ISR	8700	10.0	34	10.0	Ground-Based Systems	None	0
RQ-21 Blackjack	ISR	100	1.0	16	6.7	Ground-Based Systems	None	0
scanEagle	ISR	1200	10.0	24	10.0	Ground-Based Support	None	0
RQ-170 Sentinel	ISR	2000	10.0	12	5.0	Ground-Based Support	None	0
Tethered Aerostat Radar System (TARS)	ISR	200	2.0	days/weeks	10.0	Ground-Based Support	None	0
Persistent Threat Detection System (PTDS)	ISR	10000	10.0	30days	10.0	Ground-Based Support	None	0
High Altitude Airship (HAA)	ISR	5000	10.0	weeks/months	10.0	Ground-Based and in-flight Support	None	0
MQ-4C Triton	Maritme Survilance	5100	10.0	24	10.0	Ground-Based Systems	None	0
Drone(Skyways v2.6b)	Logistic	3.1	0.0	0.5	0.2		None	0
MQ-25 Stingray	Aerial Refueling	500	2.5	4.5	1.9	Ground-Based System	None	0



Name	Mission	Sensors	Sensor Score	TRL	TRL Score	Cost (US$)
Kratos XQ-58A Valkyrie	Air Defense	ronic warfare (EW) systems/Signals intelligence	9	7	7.0	$2,500,000
Boeing MQ-28 Ghost Bat (ATS)	Air Defense			7	7.0	$3,500,000
Lockheed SR-72	Reconnaissance / Strike			5	0.0	$900,000,000
General Atomics Avenger	Reconnaissance / Strike	EO/IR/SAR	5	9	10.0	$25,000,000
Northrop X-47B	Reconnaissance / Strike	EO/IR/SAR/ESM	6	9	10.0	$1,400,000,000
Boeing X-45	Reconnaissance / Strike	EO/IR/SAR	5	7	7.0	
Low-Cost UAV Swarming Technology (LOCUST)	electronic warfare / Strike			5	0.0	$900,000
Drone (V-Bat 128)	ISR	EO/IR/SAR	5	9	10.0	$900,000
MQ-8 Fire Scout	ISR	EO/IR/SAR/Laser Designator/ESM/AIS	8	9	10.0	$16,000,000
RQ-4 Global Hawk	ISR	EO/IR/SAR/SIGINT/COMINT	8	9	10.0	$165,000,000
RQ-21 Blackjack	ISR	EO/IR/SAR/SIGINT/COMINT	8	9	10.0	$4,000,000
scanEagle	ISR	EO/IR/SAR	5	9	10.0	$4,000,000
RQ-170 Sentinel	ISR	EO/IR/SAR	5	classified		
Tethered Aerostat Radar System (TARS)	ISR	RADAR/EO/IR/COMINT	10	Depends		$500,000,000
Persistent Threat Detection System (PTDS)	ISR	RADAR/EO/IR/COMINT	10	9	10.0	$20,000,000
High Altitude Airship (HAA)	ISR	RADAR/EO/IR	9	7	7.0	$900,000,000
MQ-4C Triton	Maritme Survilance	EO/IR/MFAS/AIS	6	8	7.5	$190,000,000
Drone(Skyways v2.6b)	Logistic			8	7.5	$400,000
MQ-25 Stingray	Aerial Refueling	None		7	7.0	$125,000,000

Name	Mission	GMBA Score	Deny Score	Control Score	Sustain Score
Kratos XQ-58A Valkyrie	Air Defense	6.5	5.8	6.5	2.5
Boeing MQ-28 Ghost Bat (ATS)	Air Defense	3.1	5.1	5.9	5.6
Lockheed SR-72	Reconnaissance / Strike	6.7	0.0	10.0	2.7
General Atomics Avenger	Reconnaissance / Strike	7.8	8.4	8.4	5.5
Northrop X-47B	Reconnaissance / Strike	7.0	0.0	5.4	5.4
Boeing X-45	Reconnaissance / Strike	6.7	0.0	7.4	3.4
Low-Cost UAV Swarming Technology (LOCUST)	electronic warfare / Strike	0.0	0.0	3.3	0.1
Drone (V-Bat 128)	ISR	3.1	0.0	4.8	3.8
MQ-8 Fire Scout	ISR	3.2	0.0	2.8	2.7
RQ-4 Global Hawk	ISR	8.4	0.0	5.8	8.3
RQ-21 Blackjack	ISR	3.3	0.0	3.9	3.9
scanEagle	ISR	3.3	0.0	5.0	4.7
RQ-170 Sentinel	ISR	8.3	0.0	8.3	3.3
Tethered Aerostat Radar System (TARS)	ISR	4.2	0.0	4.2	6.7
Persistent Threat Detection System (PTDS)	ISR	3.6	0.0	3.1	7.2
High Altitude Airship (HAA)	ISR	7.3	0.0	4.3	9.3
MQ-4C Triton	Maritme Survilance	7.6	0.0	6.3	7.7
Drone(Skyways v2.6b)	Logistic	1.5	0.0	4.8	2.7
MQ-25 Stingray	Aerial Refueling	0.0	0.0	2.8	2.8

Table 17. Value Scoring of Surface Platforms

Platform	Sensing		Shooting		Survivability		Sustainment		Totals
	Range (km)	Rank	Yield (lbs tnt)	Rank	Kinetic Protection (hide/defend itself)	Rank	# of shots/hrs run time	Rank	
LMACC w/LRASM, SLQ32, SPS73, and Ultra 2500	111.3	1.601439	1000	1.25	6	6	120	1.785714	4.637153
Ukraine type USV w/ Ultra 2500 and explosives	18.55	0.266906	441	0.55125	0	0	60	0.892857	1.711014
Sail drone	5.565	0.080072	0	0	1	1	672	10	10.08007
Protector USV w/nav radar and spike missile	22.2	0.319424	20	0.025	4	4	13	0.193452	0.537877
Narco sub type USV with Ultra 2500 and Explosives	22.2	0.319424	8000	10	0	0	120	1.785714	12.10514
CB1250 data buoy w/slq 32	22.2	0.319424	0	0	0	0	672	10	10.31942
AN/TPS 59 land EW	695	10	0	0	2	2	24	0.357143	10.35714
AN/TPS 77 land towed array	300	4.316547	0	0	0	0	24	0.357143	4.67369
Hammerhead Mine	14.84	0.213525	238	0.2975	0	0	672	10	10.51103
Hellfire missile on LMACC	8	0.115108	20	0.025	0	0	0.05	0.000744	0.140852
MK68 Mine	0.1	0.001439	2000	2.5	0	0	672	10	12.50144
Manta Mine	0.1	0.001439	309	0.38625	0	0	372	5.535714	5.923403
LRUSV	22.4	0.322302	22	0.0275	3	3	120	1.785714	2.135516
Missile Barge Anti Air Essm	100	1.438849	90	0.1125	8	8	120	1.785714	3.337063
Missile Barge LRASM	100	1.438849	1000	1.25	2	2	120	1.785714	4.474563
Missile Barge hellfire	100	1.438849	20	0.025	2	2	120	1.785714	3.249563

Table 18. Value Scoring of Undersea Platforms

Name	Speed (knots)		Speed Score	Depth (m)		Depth Score	Weight (kg)	Weight Score	Fuel Type	Fuel Type Score
	Max	Normal		Max	Normal					
Remus 100	6	4	7.06	120	100	2.40	37	10	Electric Battery	6
Remus 100-S	2.6	??	3.06	120	100	2.40	45	10	Electric Battery	6
Remus 100-M	4.5	??	5.29	120	100	2.40	39	10	Electric Battery	6
ORCA XLUUV	8	3	9.41	3000		10.00	45360	2	Electric Battery with Diesel Recharging	7
Slocum Glider (Electric) (G3)	2	1	2.35	1200		10.00	60	10	Thermal Engine	10
Slocum Glider (Thermal)	0.7	0.7	0.00	1000		10.00	70	10	Electric Battery	6
Liberdade class underwater glider	3	3	3.53	300	??	6.00	??	2	Electric Battery	6
Talisman	5		5.88	300		6.00	1800	5	Electric Battery	6
Hugin	6		7.06	4500		10.00	1550	5	Electric Battery	6
Knifefish	3	2	3.53	1400	variable	10.00	910	5	lithium ion battery	6
Bluefin 21 (new Knifefish)	5	3	5.88	1400	variable	10.00	1600	5	Li ion	6

Name	Endurance	Endurance Score	Weapons	Weapons Score	Sensors	Sensors Score
Remus 100	22 h @ 3 knts	1.53	None	0	Imaging Sonar, Optical Imaging,	5
Remus 100-S	10 h @ 3 knts	0.69	None	0	Imaging Sonar, Swath Bathymetry System, Optical Imaging,	5
Remus 100-M	10 h @ 3 knts	0.69	None	0	Imaging Sonar, ADCP/DVL, Optical Imaging,	5
ORCA XLUUV	Several Months @ 3knts	8.00	Torpedo, Mines, Tomahawks	10		10
Slocum Glider (Electric) (G3)	5 years	10.00	None	0	CDT	5
Slocum Glider (Thermal)	18 months	10.00	None	0	CTD, ADCP, acoustic modem, beam attenuation meter, echo-sounder, hydrophones, optical backscatter, PAR, radiometer, turbulence, spectrophotometer (others available by request)	5
Liberdade class underwater glider	6 months	9.00	None	0	10 kHz bandwidth hydrophones	5
Talisman	24 hrs	1.67	era and warhead (primarily	5	RF surfaced, acoustic comms submerged, sonar, MCM packages	10
Hugin	72 hrs	5.00	None	0	Various Sonars, Still image Camera, Oceangraphic Data	10
Knifefish	25 hrs @ 3 kts	1.74	None	0	synthetic aperture sonar	5
Bluefin 21 (new Knifefish)	25 hrs @ 3 kts	1.74	None	0	synthetic aperture sonar	5

Name	Cost	GMBA	Deny	Control (Survive)	Endurance
Remus 100	~$50K-$200K	4.82	0.00	3.15	5.84
Remus 100-S	~$50K-$200K	3.49	0.00	1.82	5.56
Remus 100-M	~$50K-$200K	4.23	0.00	2.56	5.56
ORCA XLUUV	$621 M	9.80	9.80	9.14	5.67
Slocum Glider (Electric) (G3)	~$100K-$200K	5.78	0.00	4.12	10.00
Slocum Glider (Thermal)	~$100K-$200K	5.00	0.00	3.33	8.67
Liberdade class underwater glider	~$100K-$200K	4.84	0.00	3.18	8.33
Talisman	$200K-$500K	7.29	5.63	5.63	2.22
Hugin	$200K-$500K	9.02	0.00	7.35	5.33
Knifefish	$4M	6.18	0.00	6.18	4.25
Bluefin 21 (new Knifefish)	$4M	6.96	0.00	6.96	4.25

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